Variability of dissolved oxygen in the Canary Current Upwelling System

Eric Machu (eric.machu@ird.fr)

Xavier Capet, A.W. Tall, V. Echevin, T. Gorgues, F. Baurand, D. Dausse, T. Brochier, Y. Tremblay, P.A. Auger, S. Ndoye, A. Lazar, P. Brehmer

Workshop on “The Canary Current Eastern Boundary Upwelling System”
10-12 March 2020, Mindelo, Cabo Verde

Context: Why do we care about oxygen?

Oxygen State	$[O_2]$ ml/l	Impacts
Depleted	2-3	Biological impacts felt at behavioural level
Critical hypoxia	1-2	Organisms require physiological adaptation to survive
Hypoxic	0.5-1	Extreme stress and mortality in organisms (denitrification)
Anoxia	< 0.5	Respiration dominated by anaerobes

On average, crustaceans are more sensitive than fish, while fish are more sensitive to low O_2 levels than bivalves and gastropods

Vaquer-Sunyer & Duarte, 2008

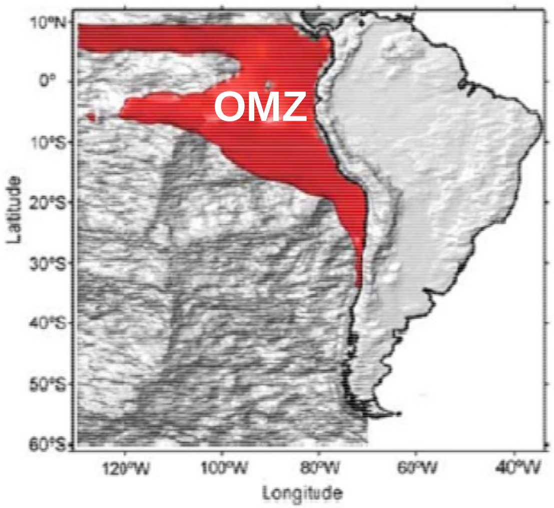
Rock lobsters, South Africa

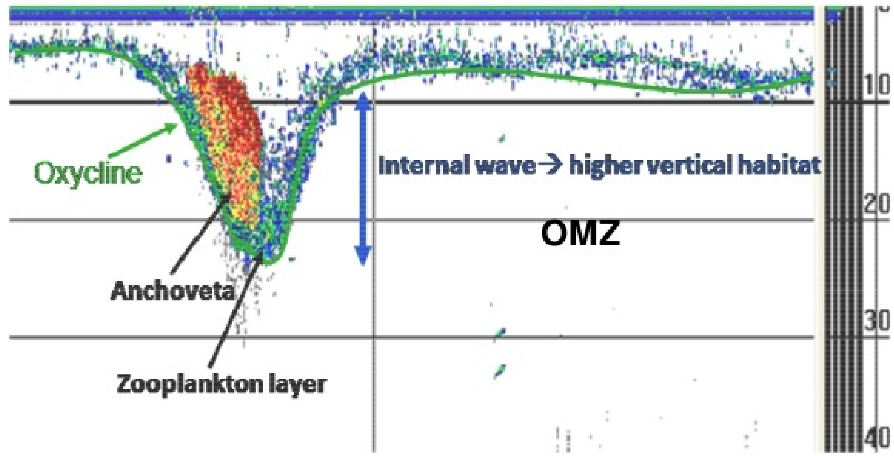
Crabs, Oregon

Fish, Mexico

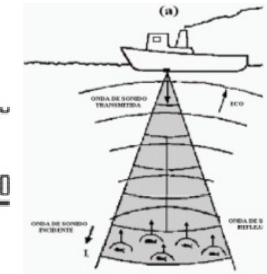
Context: Why do we care about oxygen?

DePol-Holz et al. (2007)

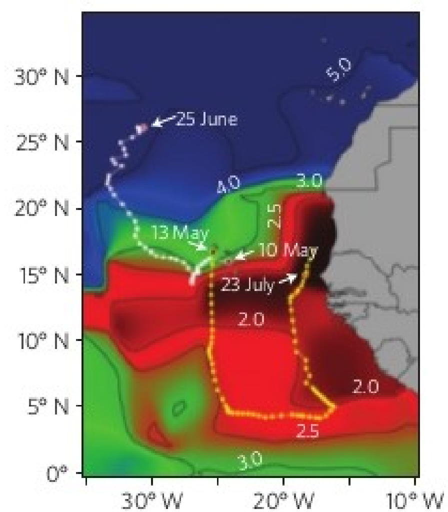




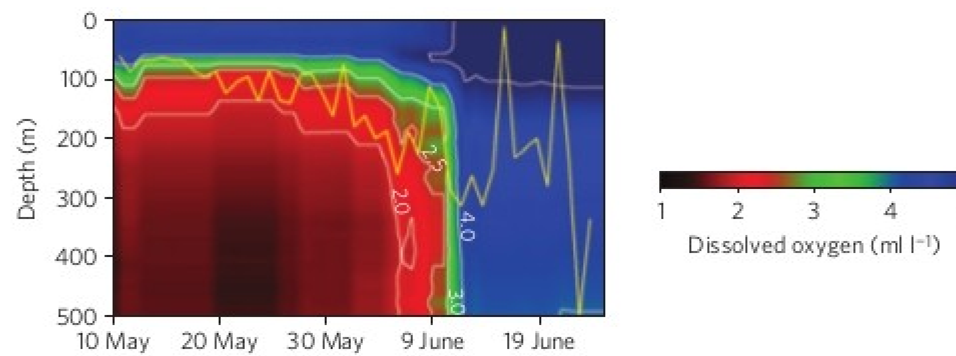
(Bertrand et al., 2008, PinO)



Oxygen defines pelagic fish habitats

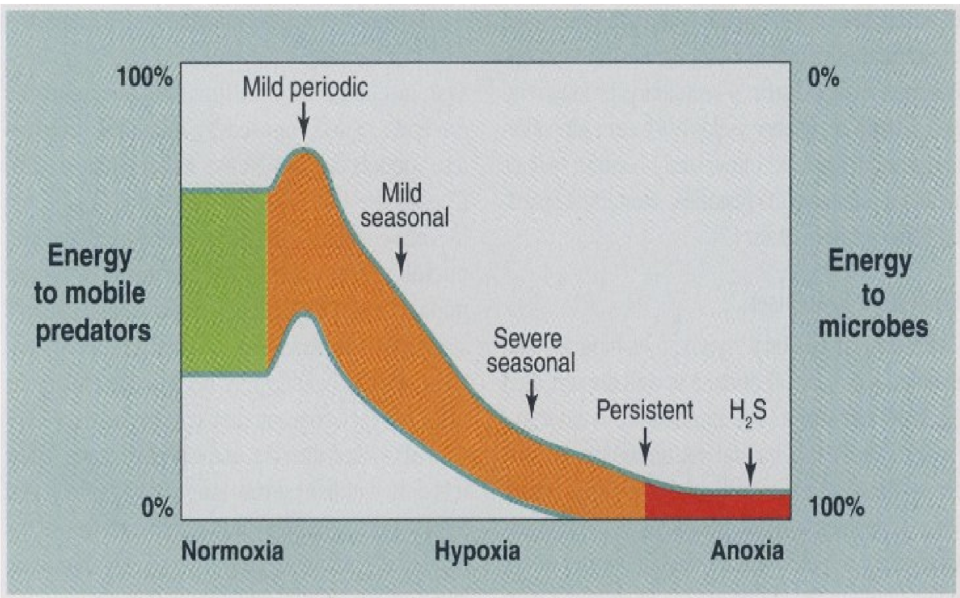


Stramma et al., 2012



Context: Why do we care about oxygen?

Benthic communities energy flow

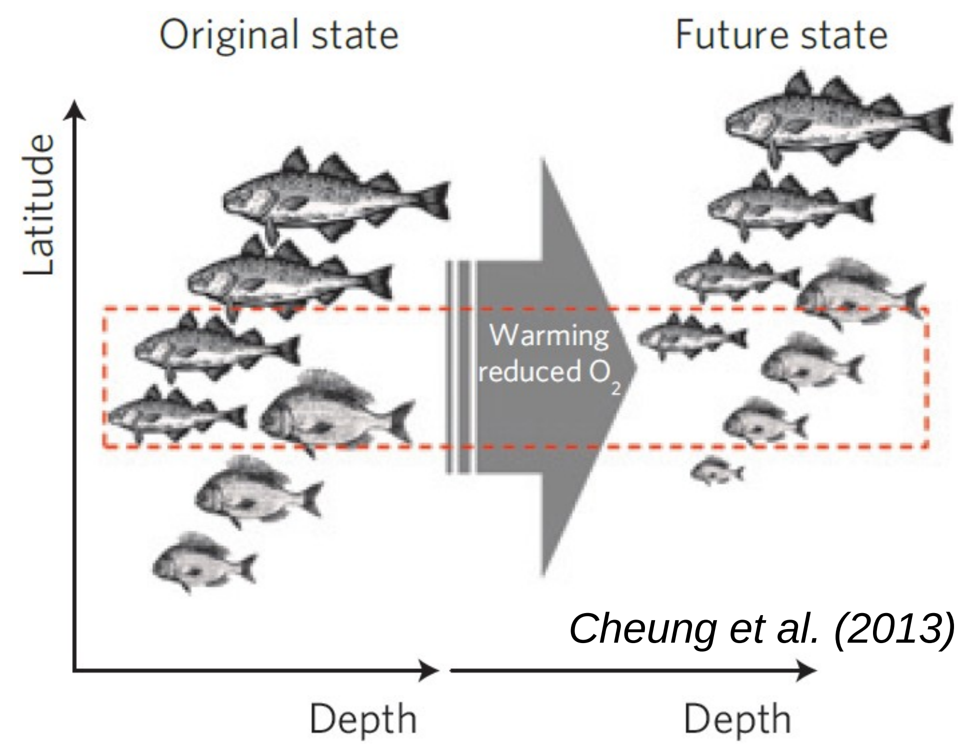


Diaz & Rosenberg (2008)

Energy transferred from the benthos to higher-level predators

- "Normaxia": 25 to 75% of macrobenthic carbon
- Mild or periodic hypoxia: pulse of benthic energy to predators
- Hypoxia: Microbes process all benthic energy as H2S, and anoxia develops

Fish



Cheung et al. (2013)

2050 horizon: 14-24% shrinking

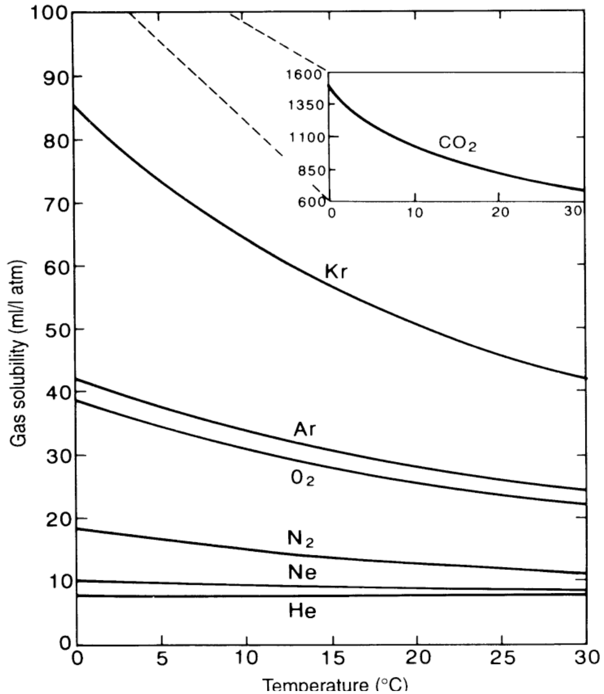
- 50% related to changes in distribution and abundance &
- 50% to physiological changes.

Tropical oceans heavily impacted

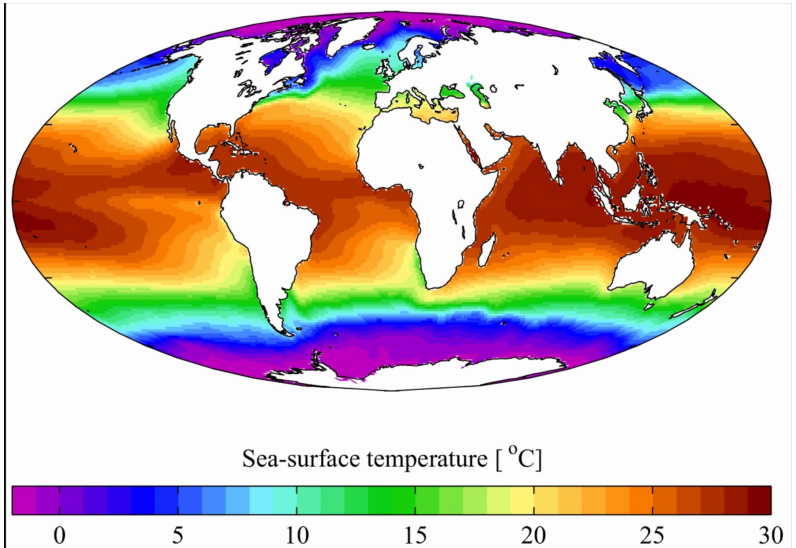
How does oxygen concentration change within the ocean?

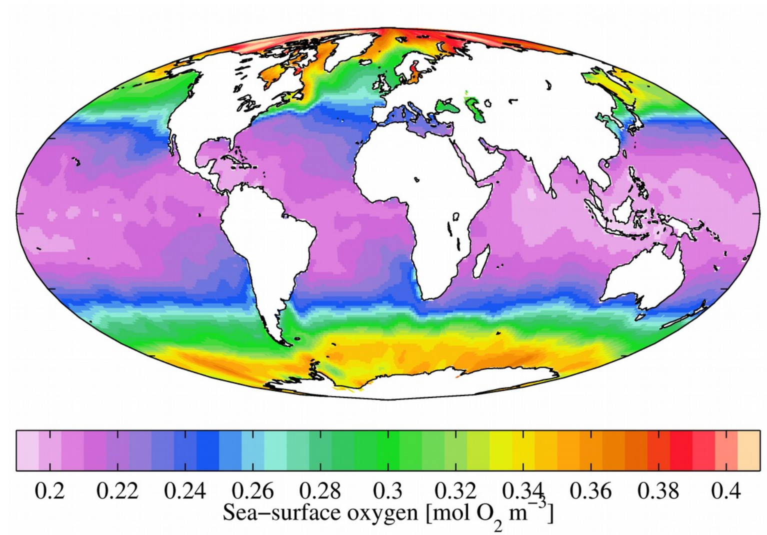
Solubility

- There is a linear solubility relationship between dissolved concentrations and partial pressure in water whose coefficient depends primarily on temperature and salinity.
- The coefficient K is expressed as a function of the Schmidt number (*Sc=v/ε* which reflects the thickness of the layer concerned in the water by the exchanges; *v* kinematic viscosity and *ε* molecular diffusivity of the gas) and of a friction velocity in the water related to the friction velocity of the wind at the surface.



Bubble exchanges play an important role for poorly soluble gases such as O_2; and may explain a slight oversaturation of ocean surfaces with oxygen (1-2%).





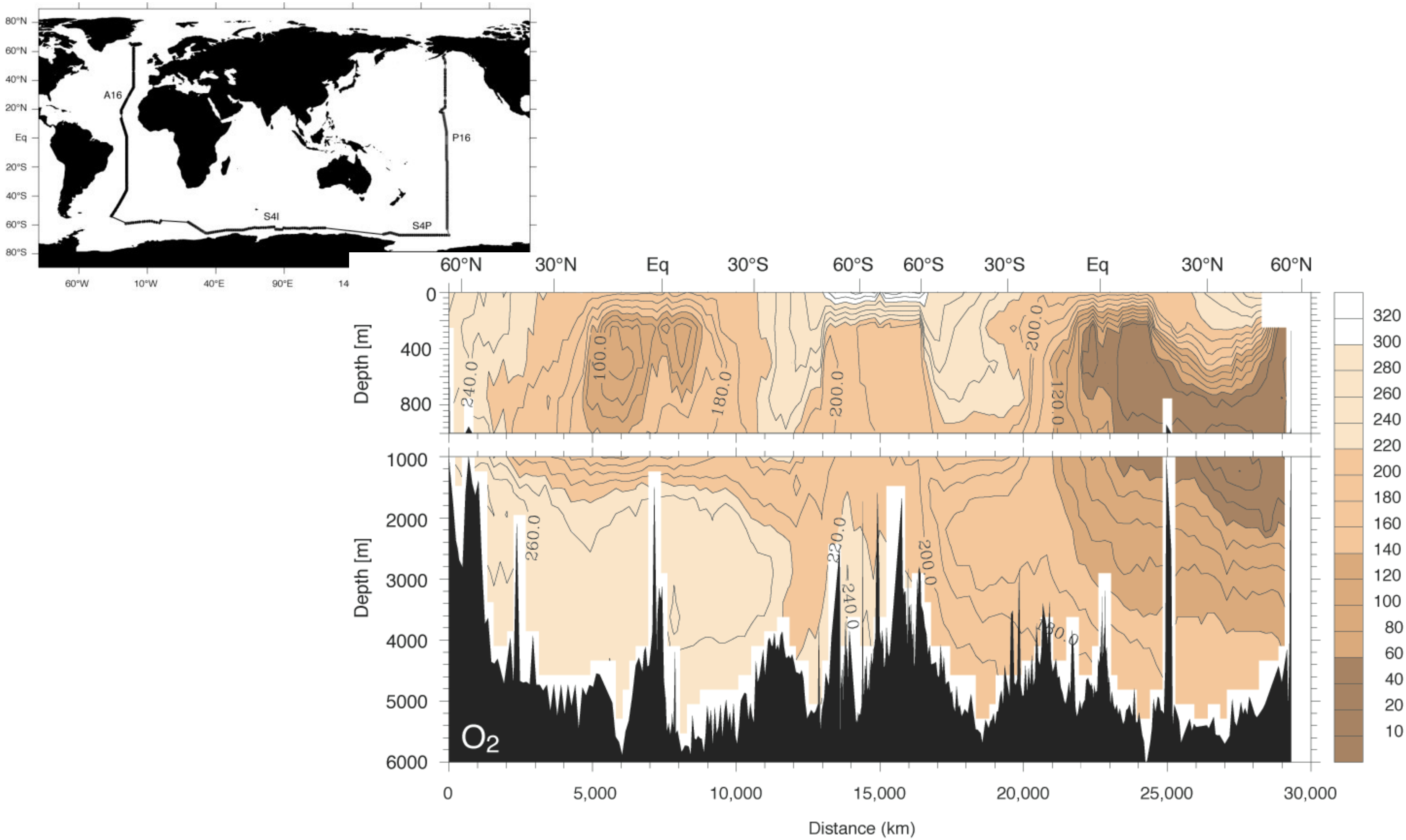
How does oxygen concentration change within the ocean?

Primary production and remineralisation

$$106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O$$
$$= (CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\ O_2$$

- Oxygen is produced during photosynthesis (can induce 3 to 10% oversaturation)
- Oxygen is consumed during respiration and remineralisation of the organic matter

How does oxygen concentration change within the ocean?



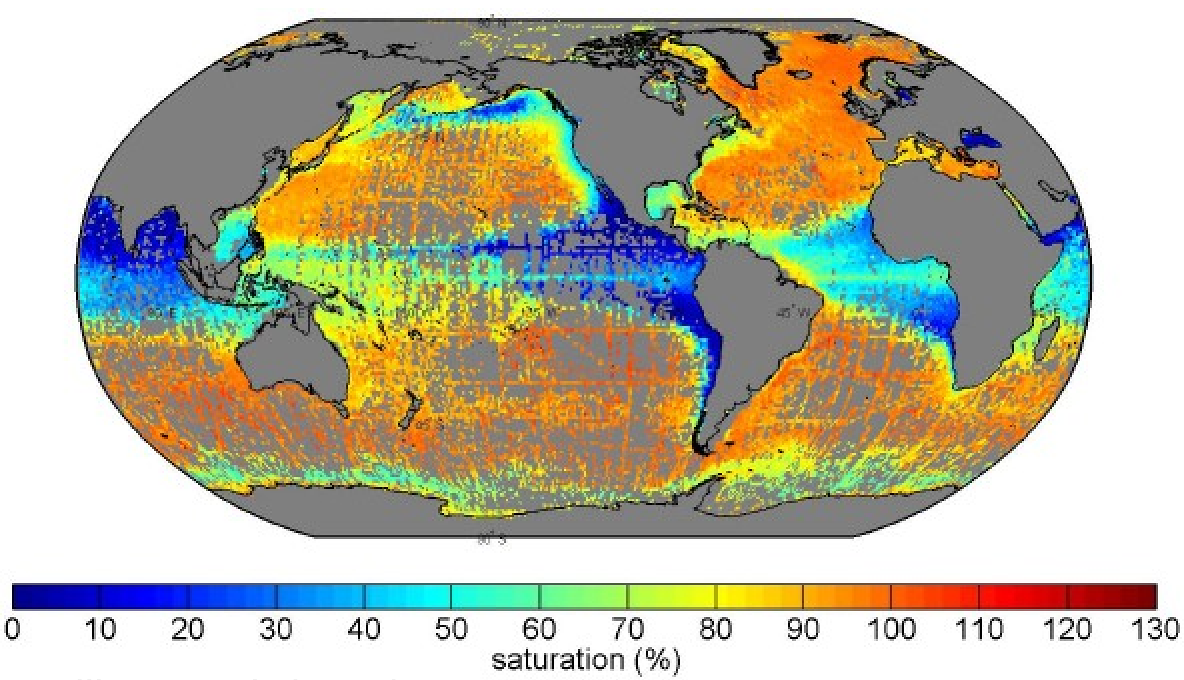
O2 concentration in the ocean interior results from water formation conditions, mixing processes between water masses and the age of the water masses (remineralization integration).

Context: Ocean is loosing and will loose breath

Deoxygenation occurs in both coastal and open oceans, the percentage of negative oxygen trends being greater in the coastal ocean (*Gilbert et al., 2010*)

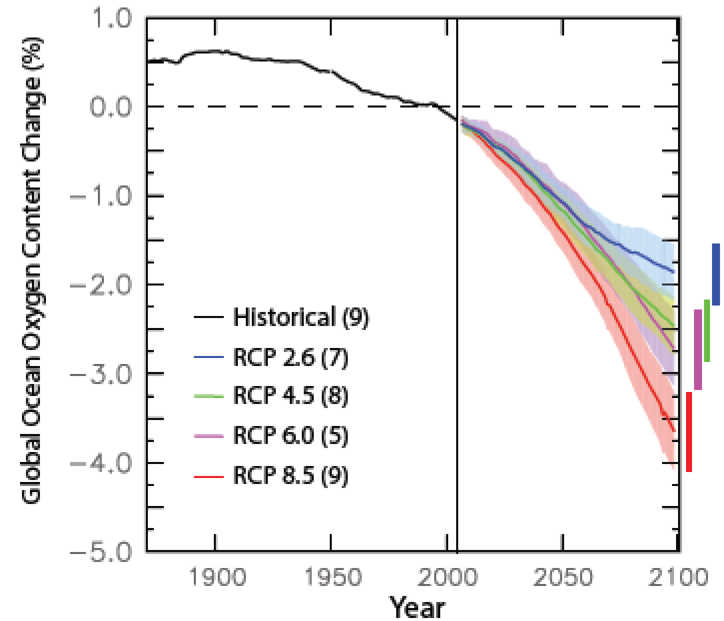
- <u>Open ocean</u> reduction processes: 1- warming-induced reduction in solubility; 2- increased stratification/reduced ventilation; 3- Carbon-to-nitrogen drawdown increase.
- <u>Coastal</u> reduction processes: 1- temperature dependent oxygen solubility; 2- **eutrophication**.

Global Ocean DO (%) at 150 m



Gilbert et al. (2010)

Simulated Global Ocean DO reduction

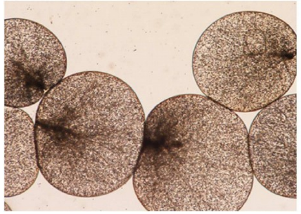


Bopp et al. (2013) from CMIP-5

Context: Ocean is loosing and will loose breath

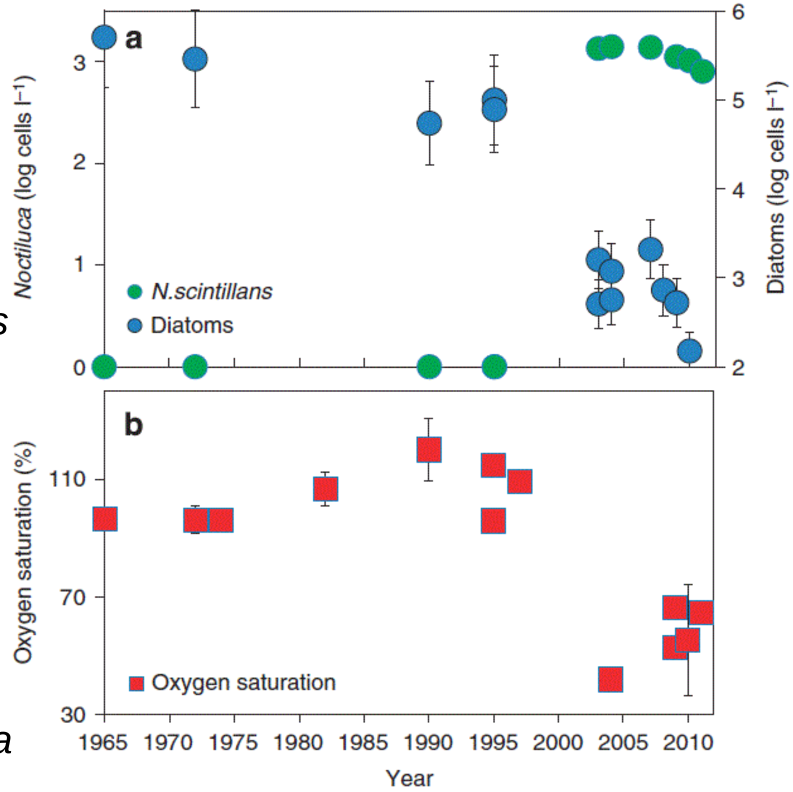
Arabian Sea exemple: Shift from diatoms to Noctiluca scintillans

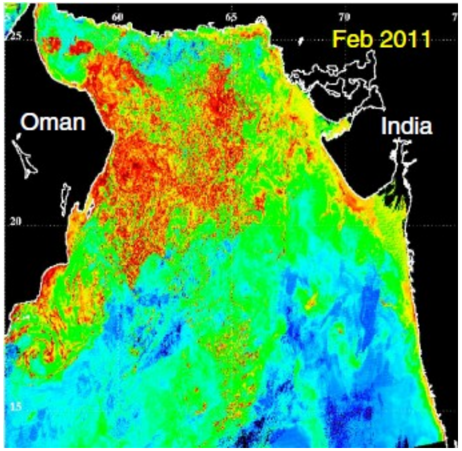
Gomez et al., Nature Com. 2014

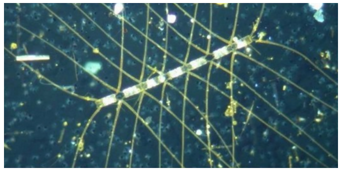


N. scintillans
~1mm

Salp
Pegea confoederata

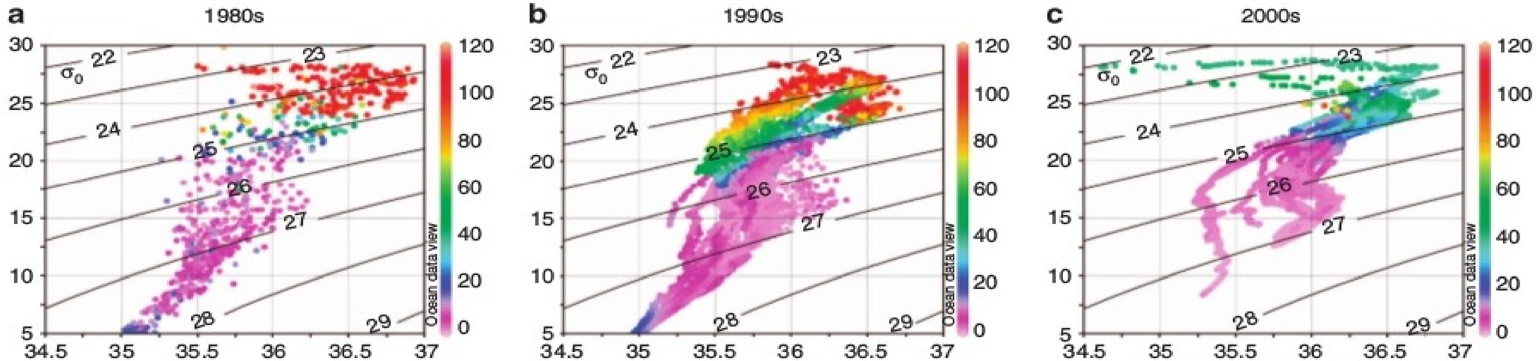






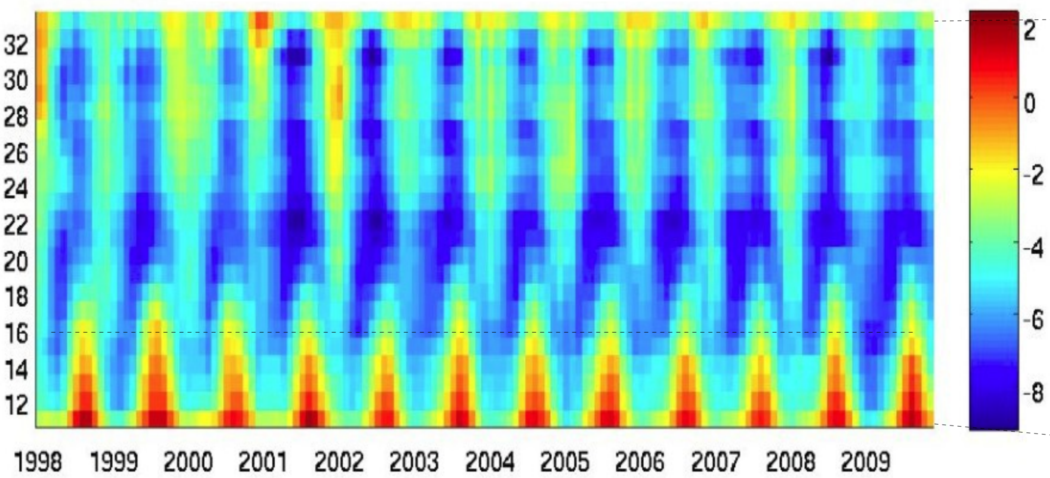
Diatoms
~10µm

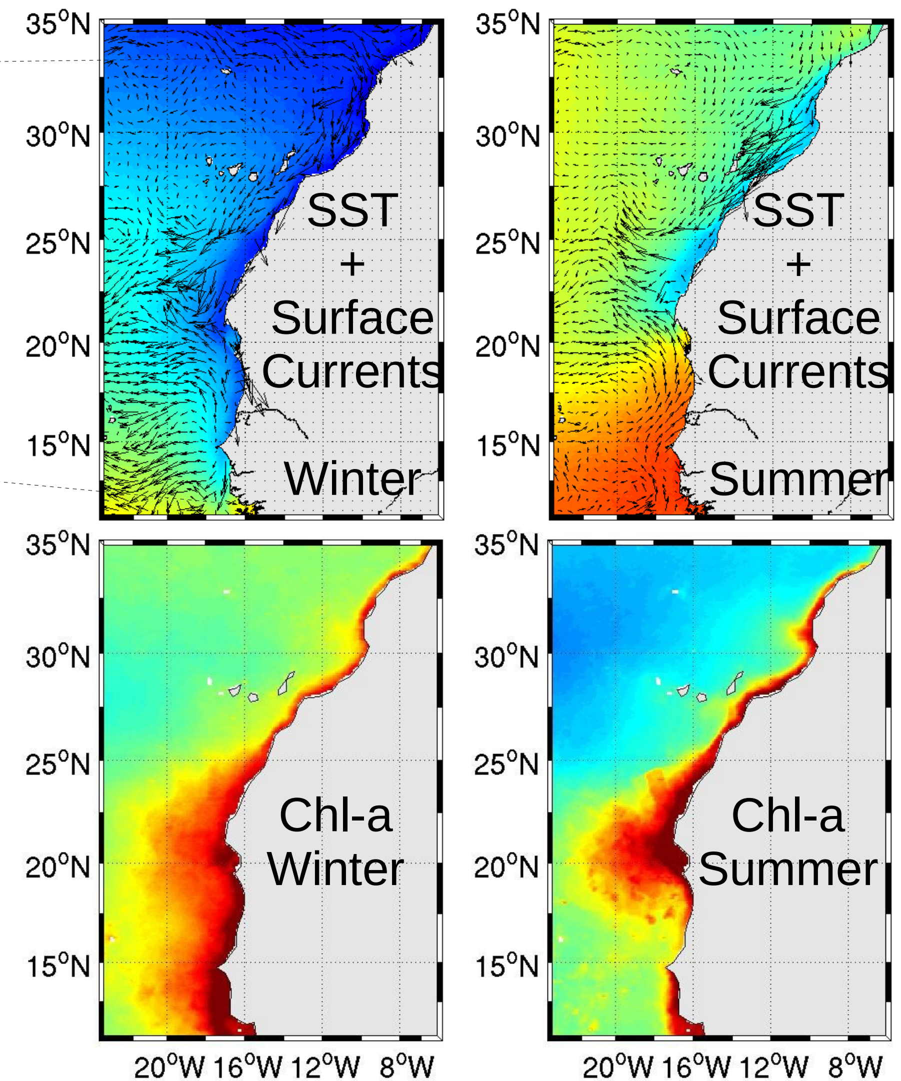
N. scintillans favored over diatoms in reduced oxygen conditions



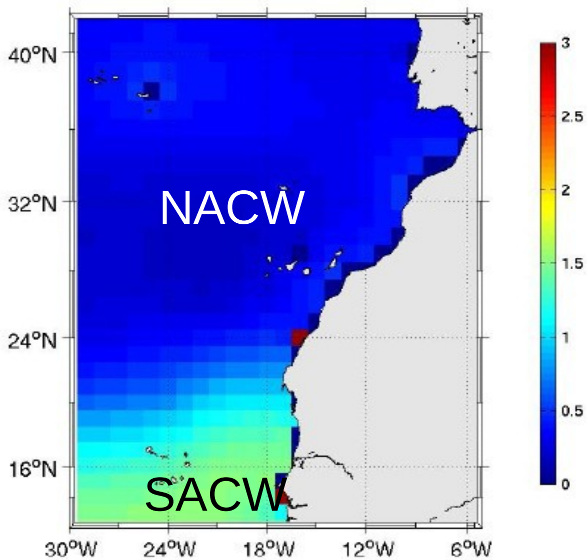
Eastern Tropical North Atlantic (ETNA)

QuikSCAT wind (1998-2009)



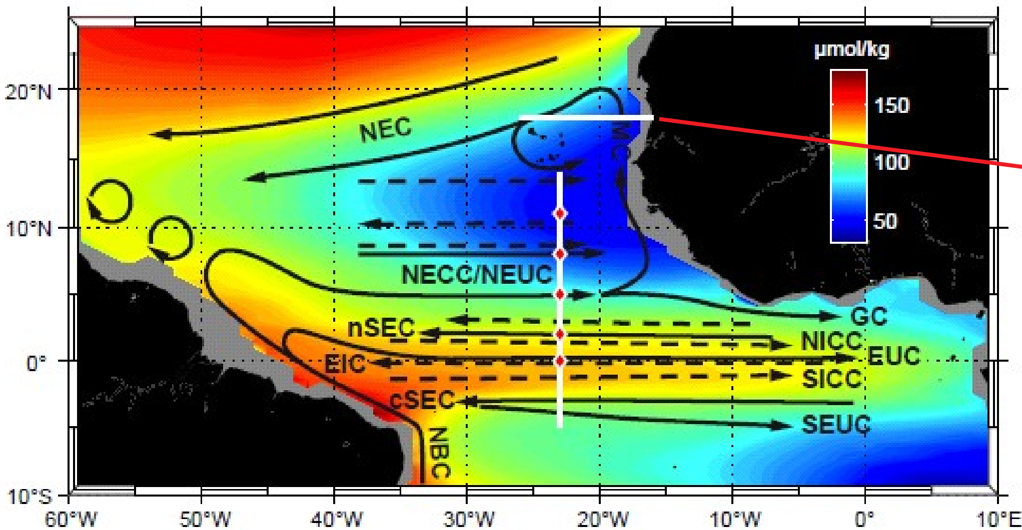


WOA – Phosphate (200 m)



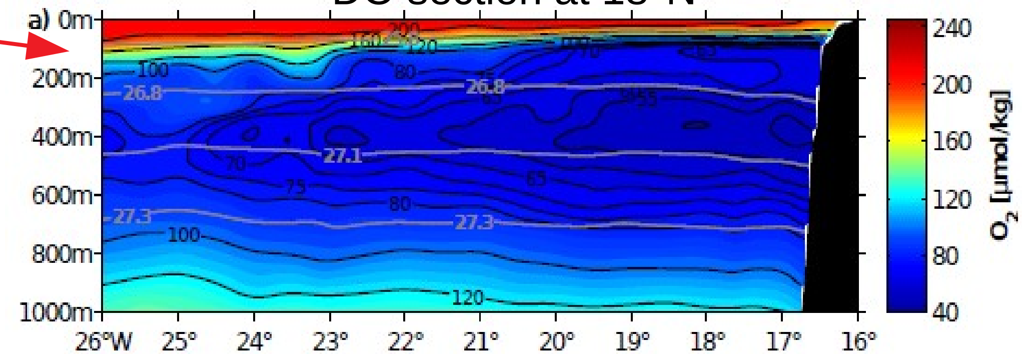
Auger et al., 2016

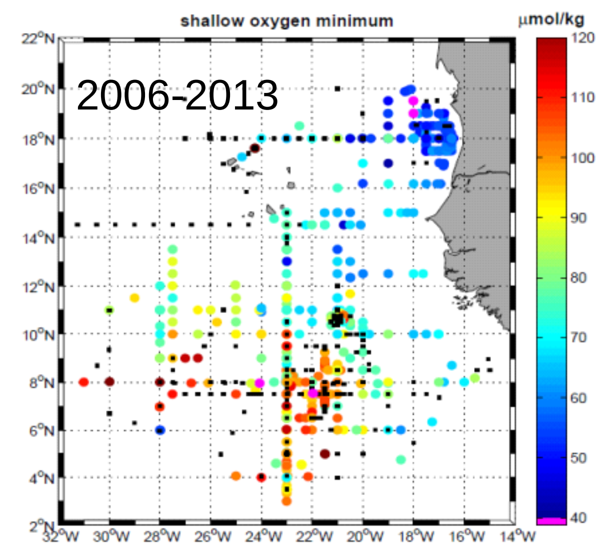
ETNA: Dissolved oxygen in the open ocean



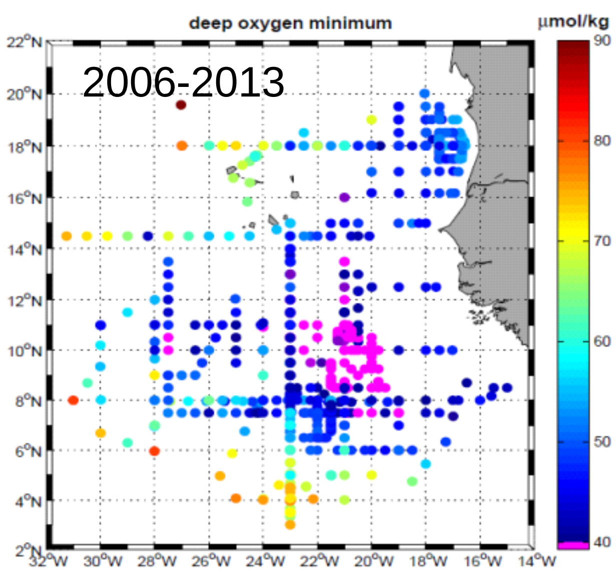
Shallow Oxygen Minimum

DO section at 18°N

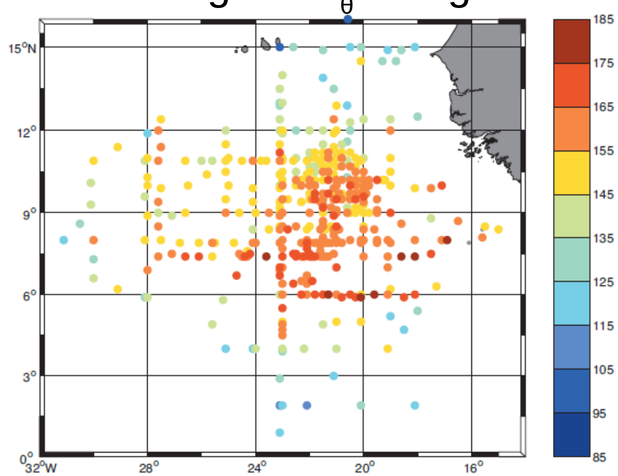




Oxygen Minimum Zone



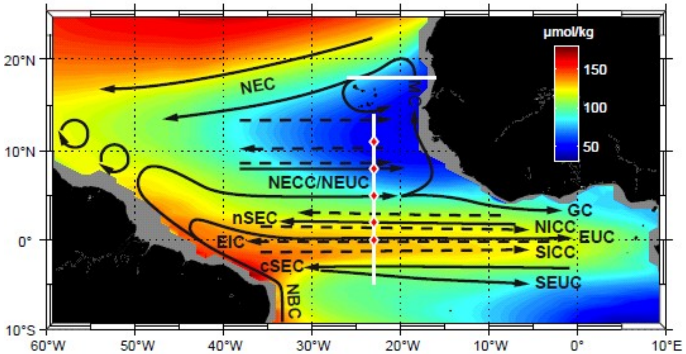
Mean age at σ_θ=27kg/m^3



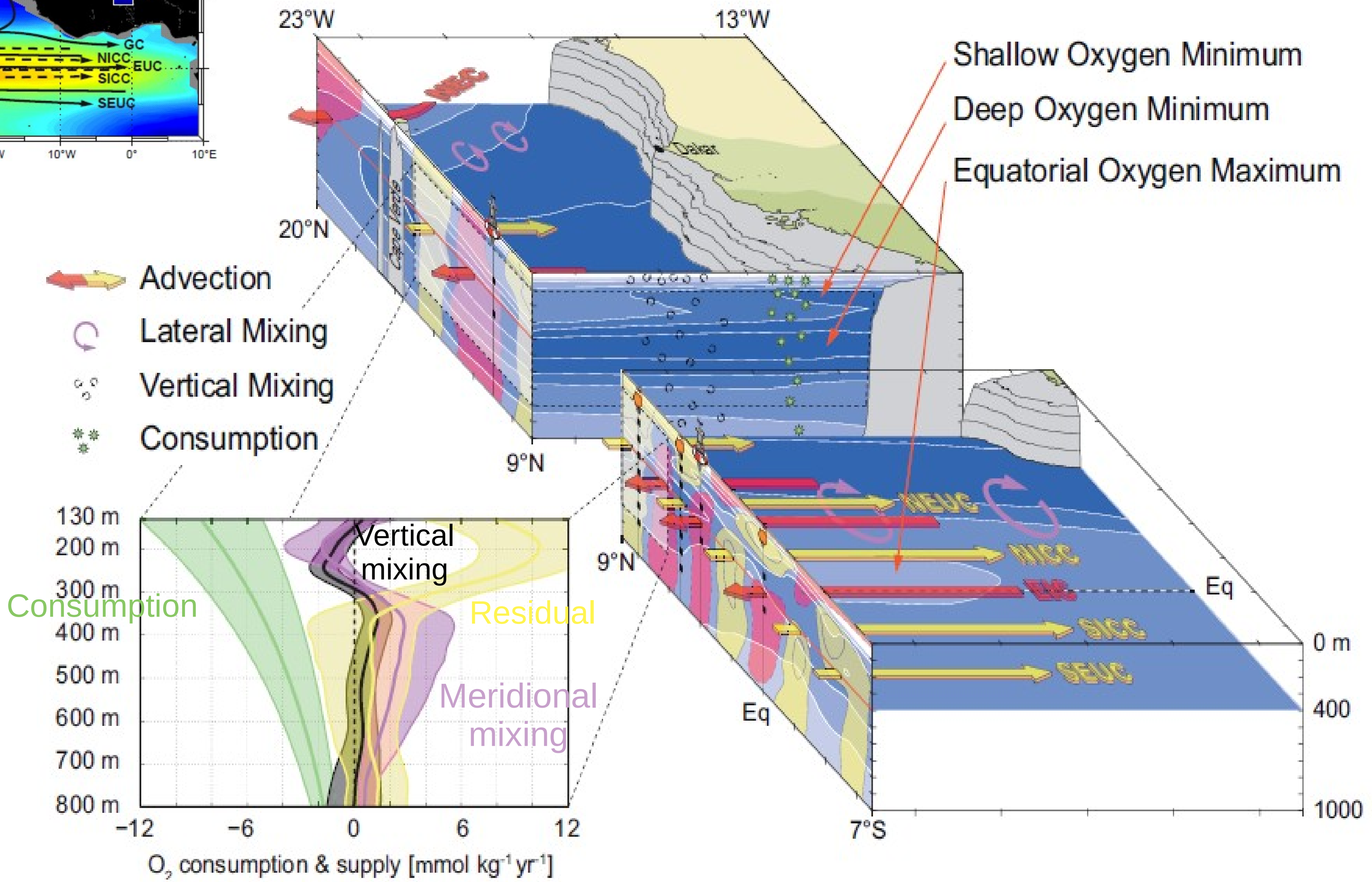
Older water masses of the deep OMZ (~120-180 yrs) compared to regions north and south of it

Brandt et al., 2015

ETNA: Dissolved oxygen in the open ocean



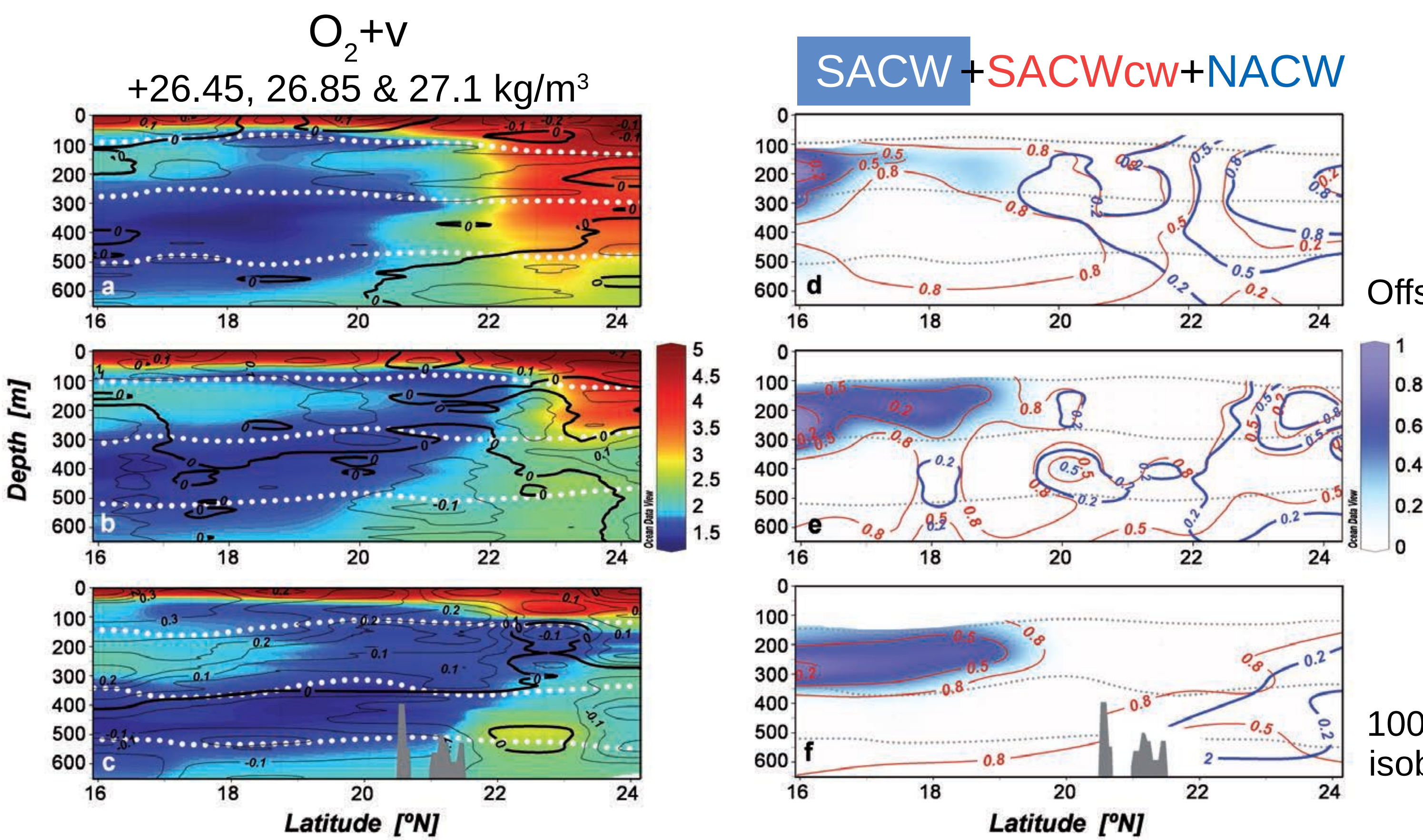
Processes involved in oxygen evolution

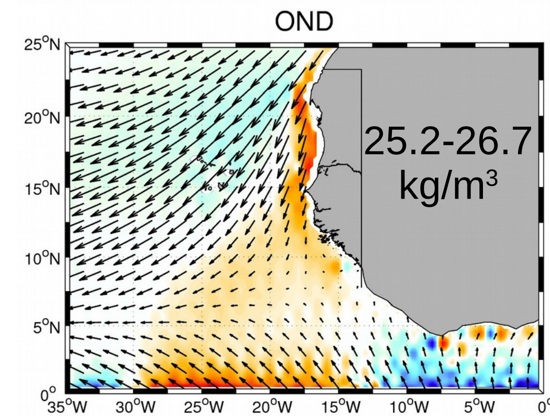


Brandt et al., 2015

ETNA: Dissolved oxygen in the open ocean

The Mauritanian or West Africa Boundary Current

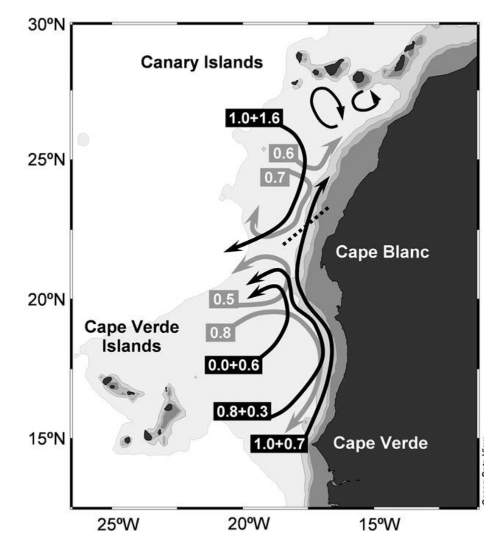




Kounta et al., 2018

SACWcw saltier and less oxygenated than SACW

Pena Izquierdo et al., 2012

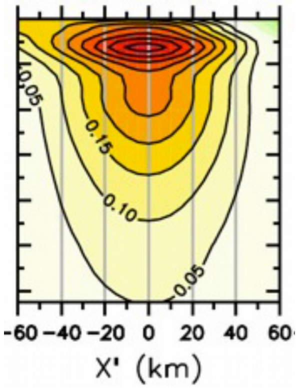


- Seasonal variability of the WABC (max in AMJ & OND)
- uCW oxygen content decrease northward (sedimentation)
- The slope system plays a significant role both in cross-CVFZ transfer & in the ventilation of the GD region, significant pathway of water mass exchange between tropical & subtropical gyres

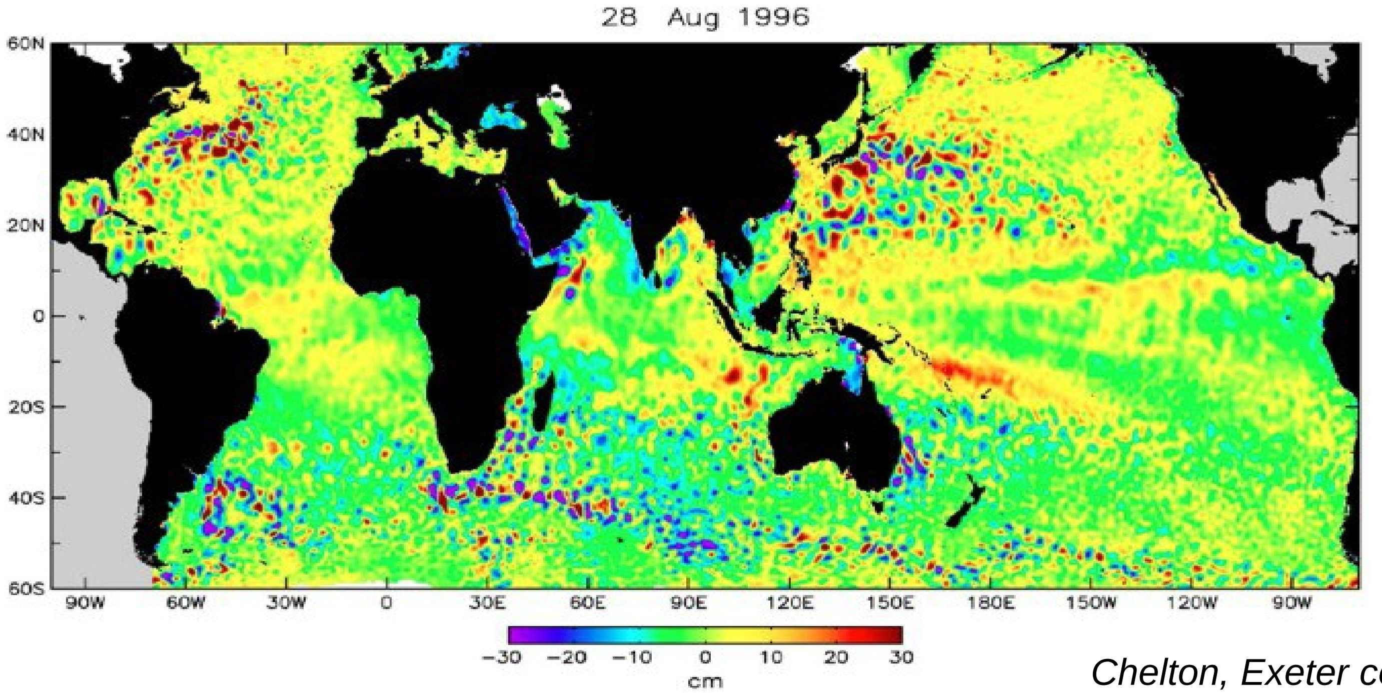
ETNA: Dissolved oxygen in the open ocean
The role of mesoscale/submesoscale activity

Mesoscale

- Forces neglected in the synoptic scale primitive equations become important at the mesoscale and all terms of the Navier-Stokes equations must be used to explain the behaviour of water patches. This includes the centripetal force and the much higher order vertical Coriolis force under mesoscale conditions, comparable to the pressure force and the horizontal Coriolis force, which can no longer be neglected.
- Cyclonic and anticyclonic eddies are Ubiquitous features in the ocean



Merged Topex & ERS 1 SSH data

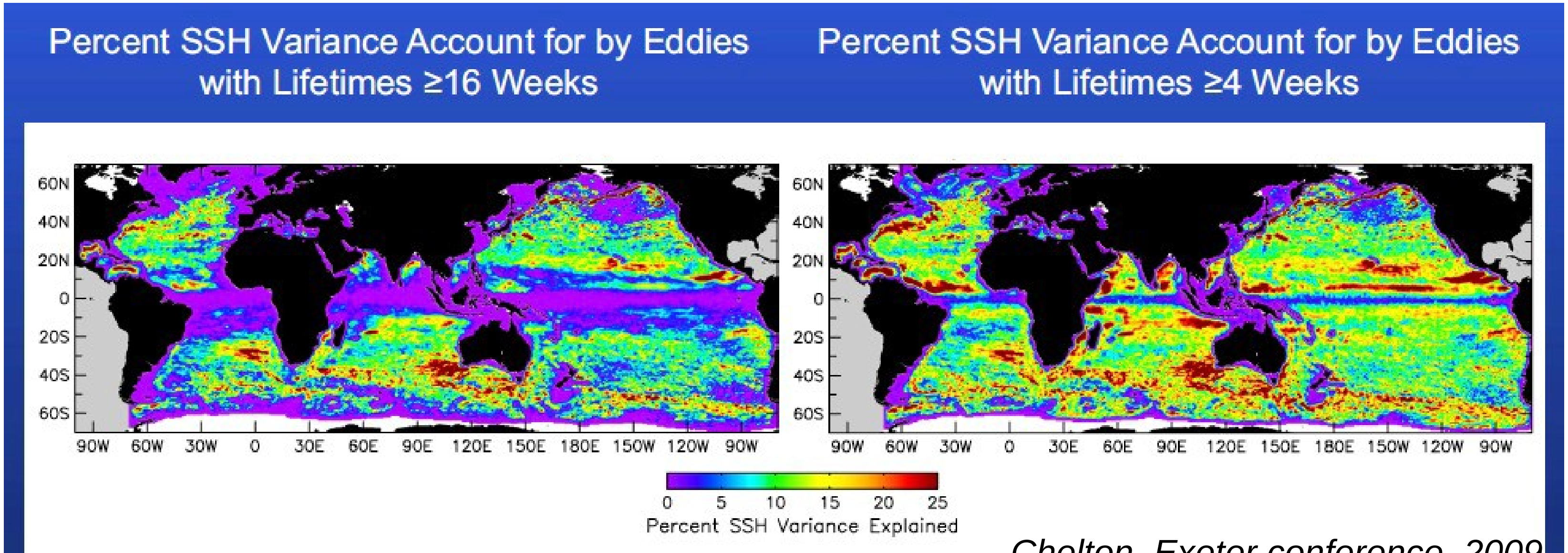


Chelton, Exeter conference, 2009

ETNA: Dissolved oxygen in the open ocean
The role of mesoscale/submesoscale activity

Mesoscale

- Velocity variance is distributed unevenly across scales: there is much more variance at scales of the order of about 50-60 km; i.e. the turbulent structures of larger size are not very energetic
- Eddies involve dynamical anomalies (such as sea surface height (SSH) and density anomalies) with large amplitudes
- Eddies are associated with a small fraction of the total SSH variance (or Eddy Kinetic Energy) but they are nonetheless considered as the key building block of oceanic turbulence in particular because they shape turbulent motions outside their core



Chelton, Exeter conference, 2009

ETNA: Dissolved oxygen in the open ocean
The role of mesoscale/submesoscale activity

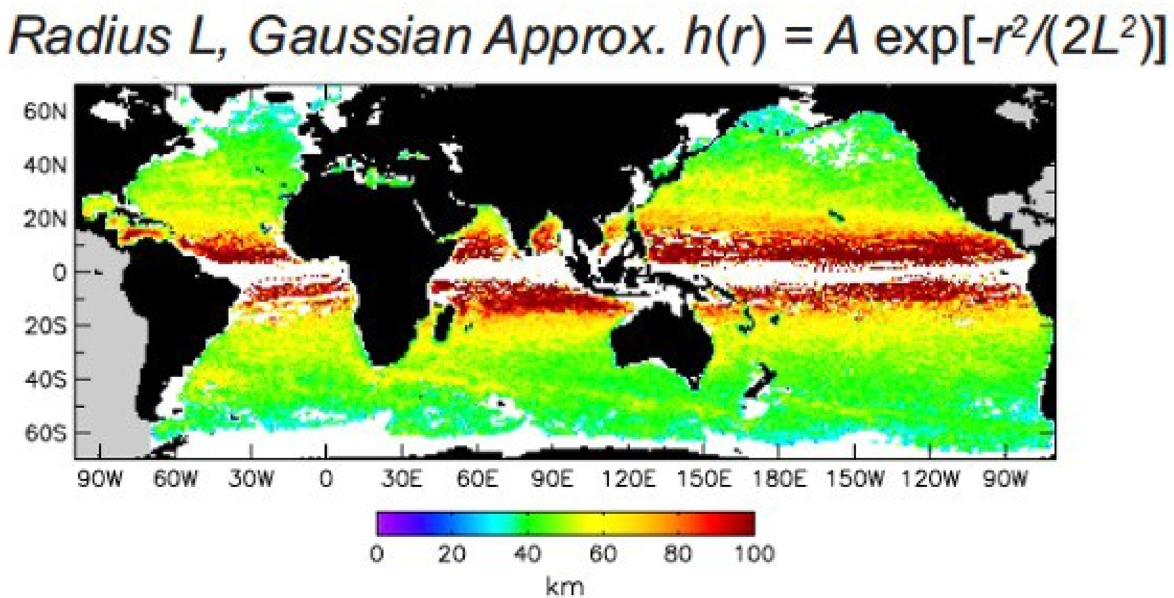
$$q = \nabla^2 \psi + \partial_z \left(\frac{f^2}{N^2} \partial_z \psi \right)$$

When adimensionalized with
L a typical length scale
for the processes of interest

$$q^* = \nabla^{*2} \psi - \frac{L^2}{R_d^2} \psi$$

L ~ Rd is a special case for which vorticity and stretching are a priori of the same order of magnitude so that potential vorticity can be exchanged between both forms. Such exchanges are key for the development of instability processes (baroclinic instability). Rd depends on 1/f

Mesoscale eddies tend to be larger in some regions

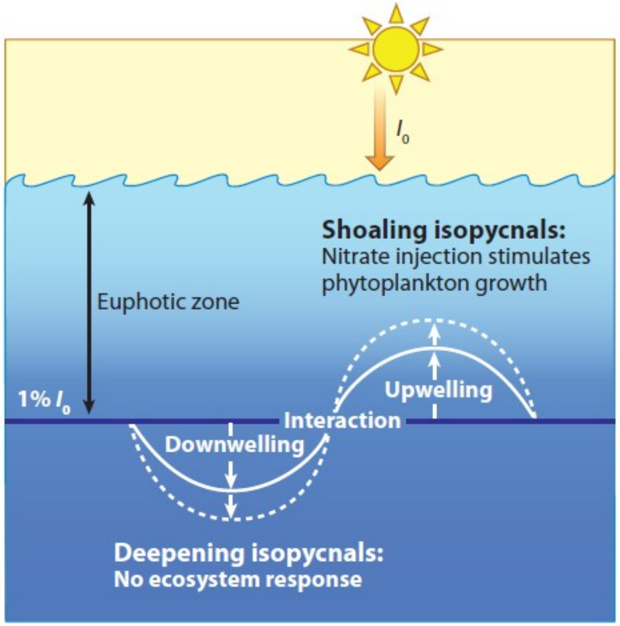


ETNA: Dissolved oxygen in the open ocean
The role of mesoscale/submesoscale activity

- Mesoscale features are associated with **vertical velocities** which give motivation to take them into account because concentrations of many oceanic tracers, such as temperature, salinity, nutrients, dissolved oxygen, and dissolved organic and inorganic carbon, change rapidly with depth just below the mixed layer.
- The vertical velocity at a given level is related to the density time evolution :

$$w = \frac{g}{\rho_0 N^2}\left(\frac{\partial \rho}{\partial t} + \vec{u} \cdot \nabla \rho\right)$$

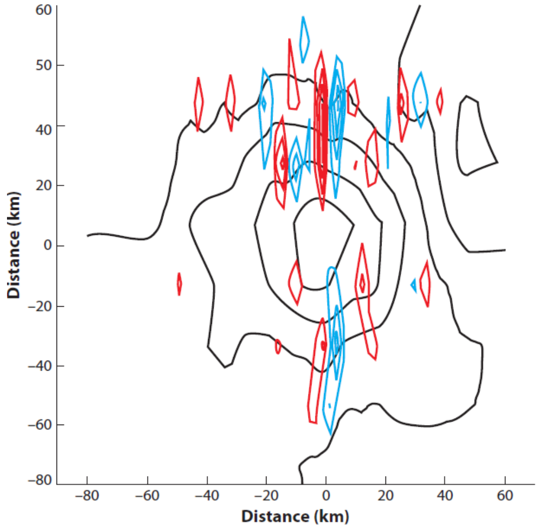
- If a surface cyclone (associated with a positive density anomaly) strengthens or an anticyclone (negative density anomaly) decays, then through this equation one can expect a positive vertical velocity inside the eddy. A negative vertical velocity would occur in the case of the decay of the cyclone



- Few modelling studies carried out in years 2000s pointed out the issue of spatial resolution for determining the mesoscale eddy contributions as sources of nitrate

ETNA: Dissolved oxygen in the open ocean
The role of mesoscale/submesoscale activity

- Former mesoscale/eddy studies implicitly assumes that the vertical exchanges occur principally in the interior of mesoscale eddies. First, this view implicitly assumes that nutrients or tracers are well mixed on isopycnals. Second, this view assumes that the space between the mesoscale eddies is a dynamical desert in terms of the vertical pump.

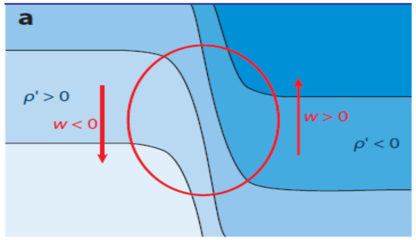


Vertical velocities can be computed from omega equation:

$$N^2\nabla^2 w + f^2 w_{zz} = -2\frac{g}{\rho_0}\nabla\cdot\vec{Q}$$

$$\text{where } \vec{Q} = -[\nabla\vec{u}]^{\mathrm{T}}\nabla\rho$$

- Looking at an eddy as a front in its radial direction, the vertical exchanges should be mostly efficient on the periphery of the eddy and not on the center



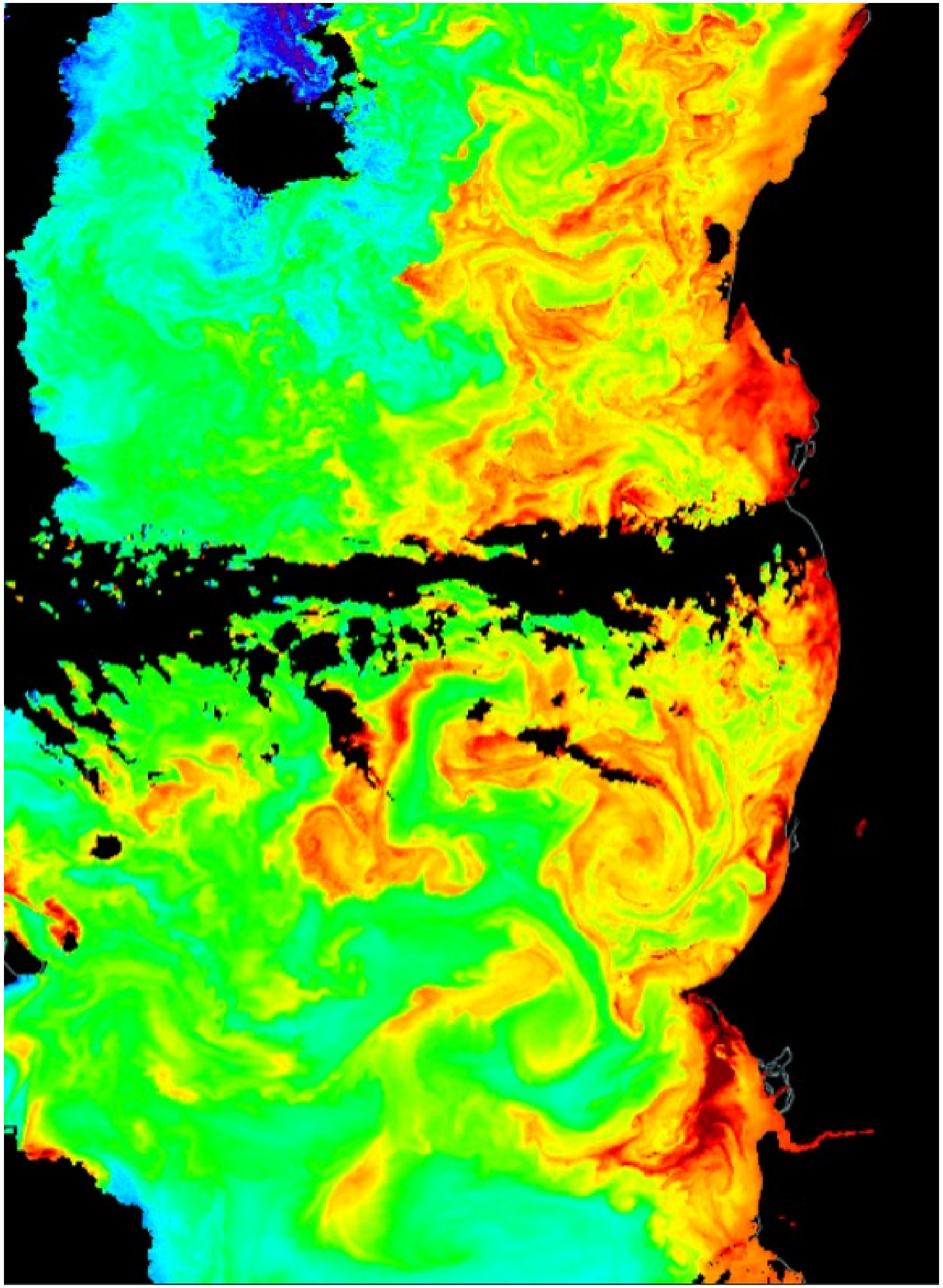
- Field observations and high resolution numerical studies contradicted the Ekman pumping paradigm that assume tracers are well-mixed over isopycnals and showed that small-scale hotspots of upwellings were located within submesoscale structures, such as filaments located outside the eddy cores

ETNA: Dissolved oxygen in the open ocean

The role of mesoscale/submesoscale activity

http://people.atmos.ucla.edu/gula/Movies/nesea_sfc_vrt.mov

ETNA: Dissolved oxygen in the open ocean
The role of mesoscale/submesoscale activity



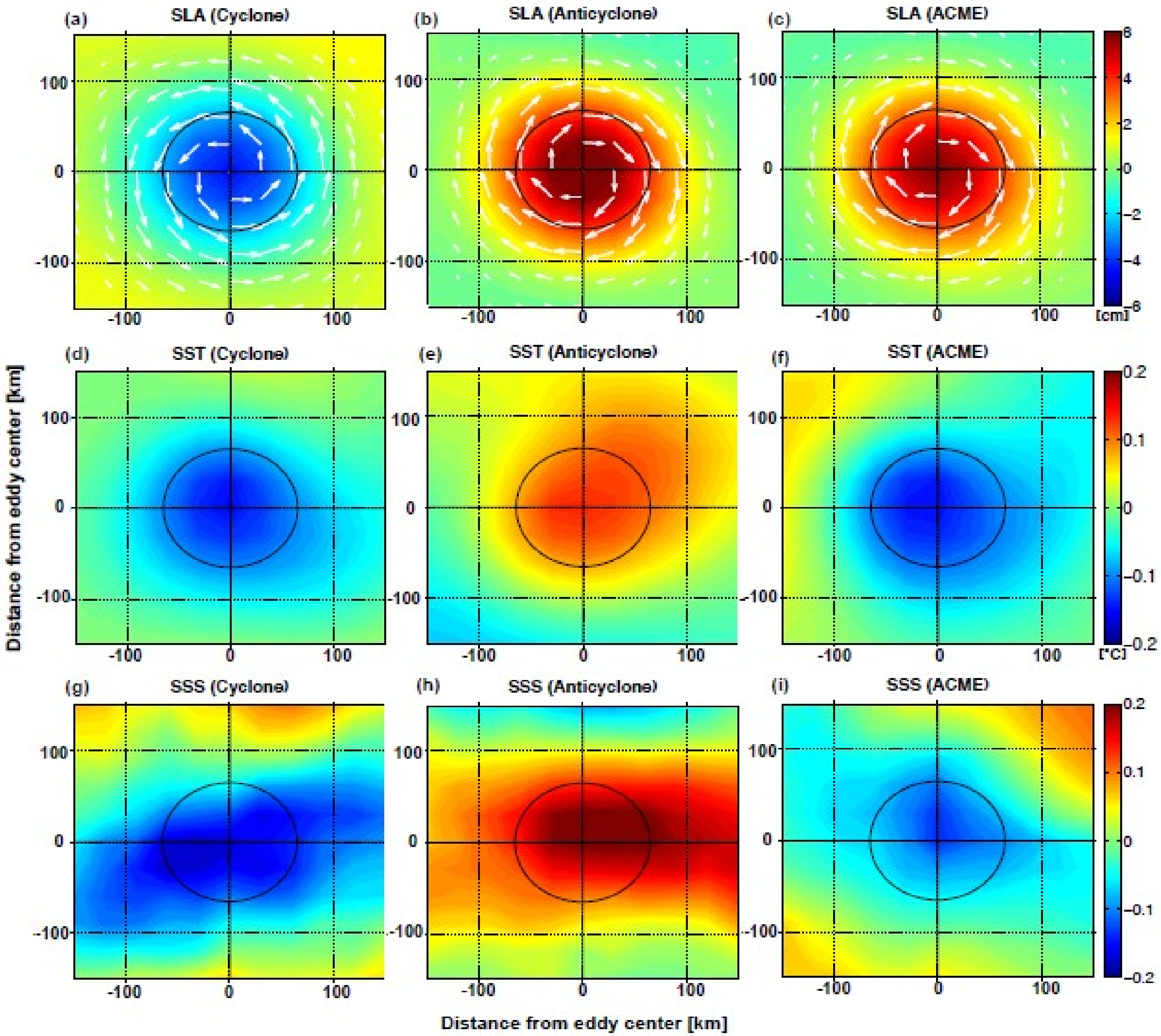
MODIS Aqua, 16 January 2020

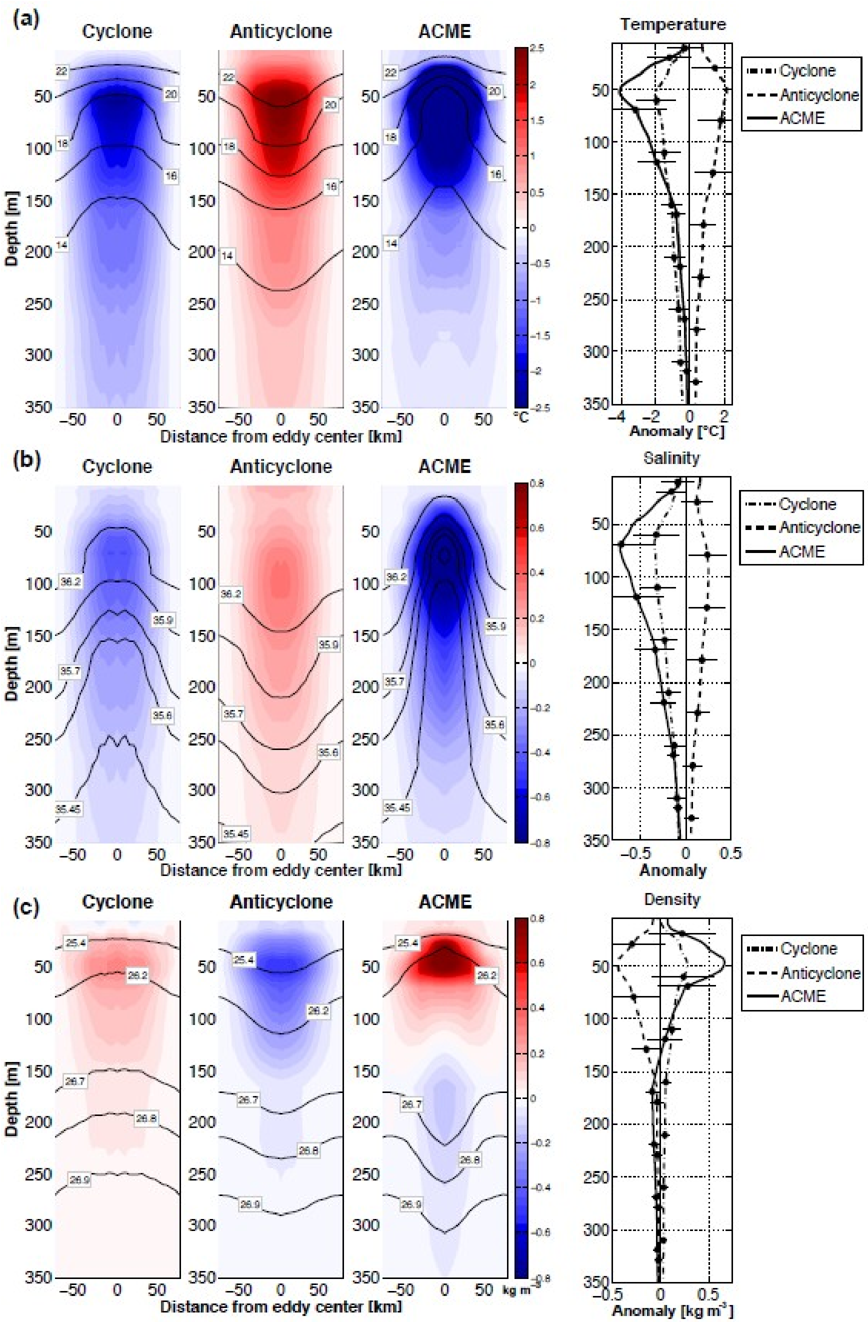
- Mesoscale variability in upwelling systems is produced mainly through baroclinic instability of the coastal upwelling jet. In terms of energy, the wind drives available potential energy in the coastal area which is then transformed into eddy kinetic energy during the baroclinic instability process. The amount of energy conversion varies with the available potential energy, or equivalently, with vertical shears of the coastal jet
- Topography also impact frontal formation and mesoscale activity

ETNA: Dissolved oxygen and eddies

Three types of eddies in the ETNA

Cyclones | Anticyclones | Anticyclonic Mode Water Eddies

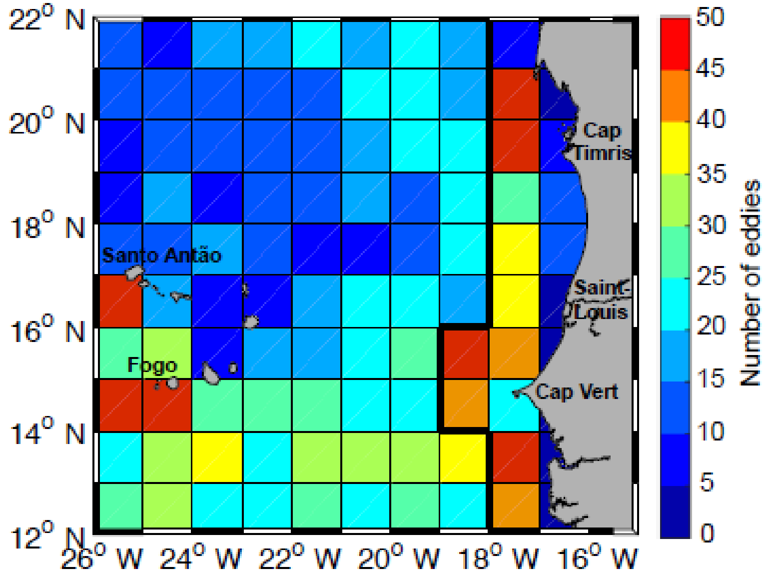




Schutte et al., 2016b

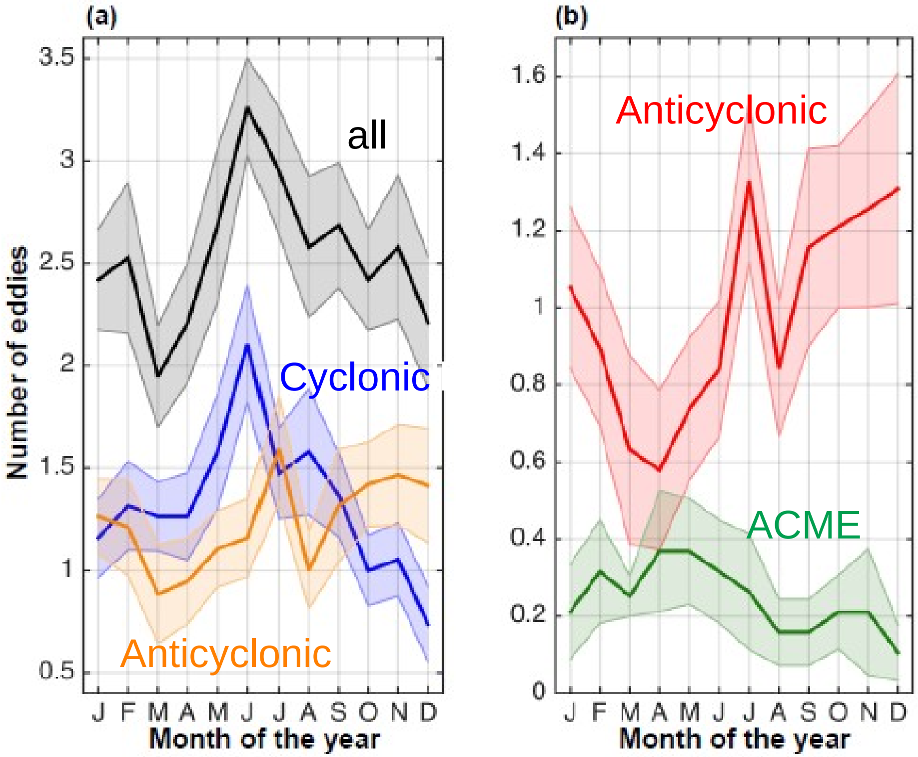
ETNA: Dissolved oxygen and eddies

Eddies number
1995-2003



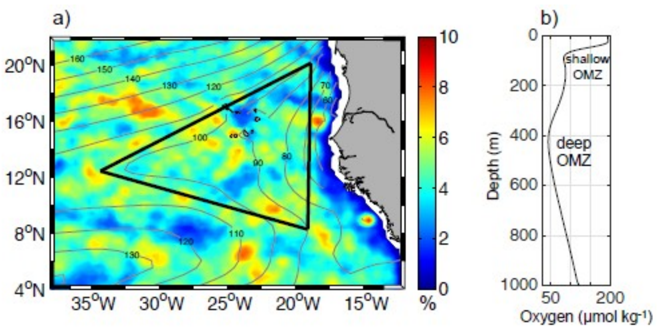
Schutte et al., 2016b

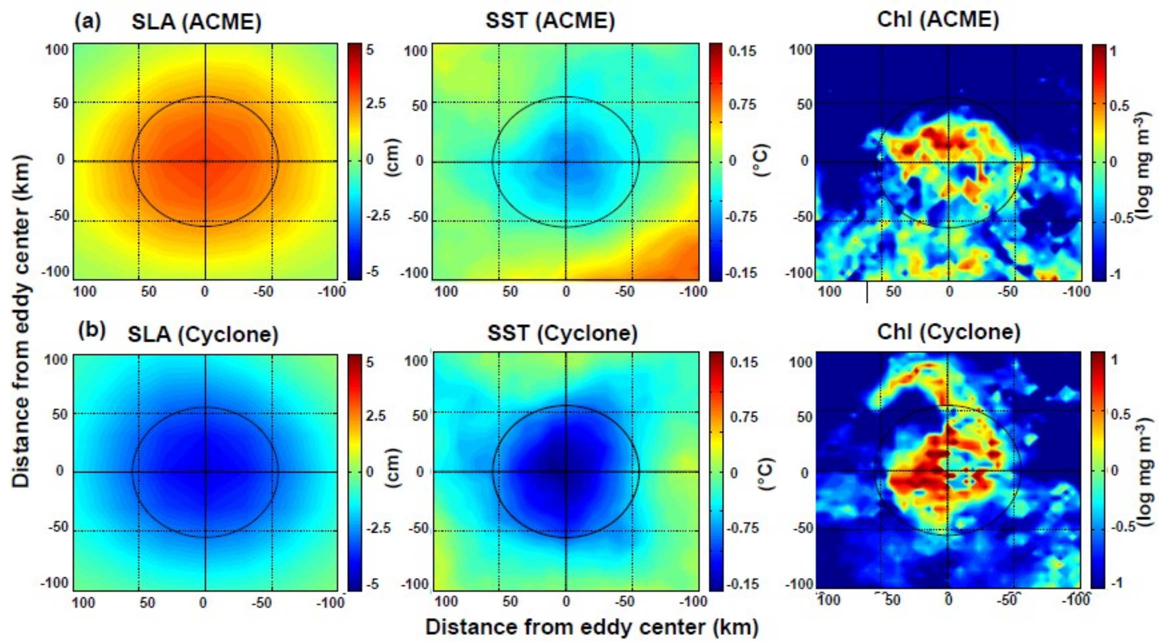
Seasonality

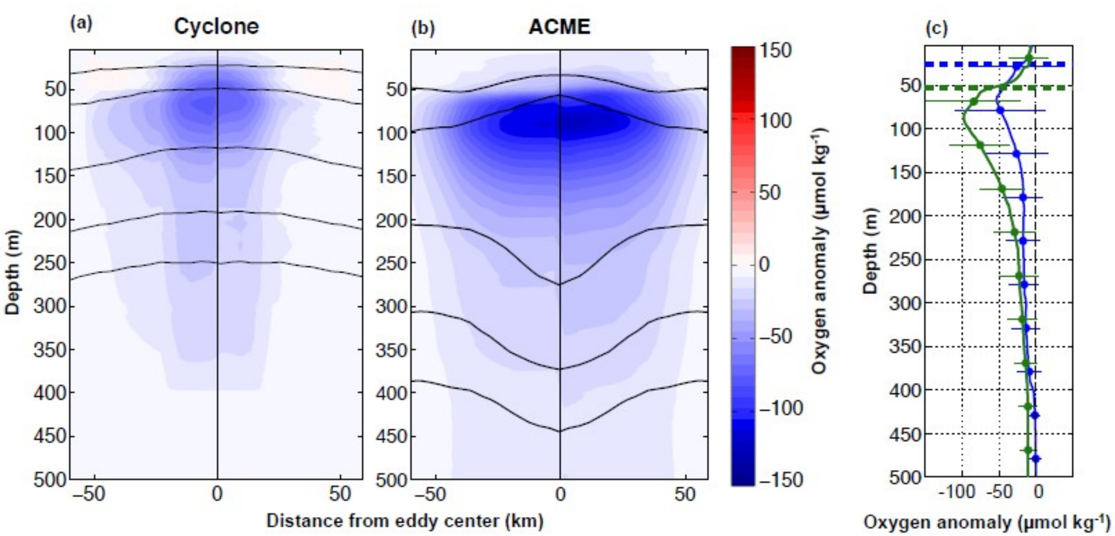


ETNA: Dissolved oxygen and eddies

“Dead-zone” eddy coverage per year



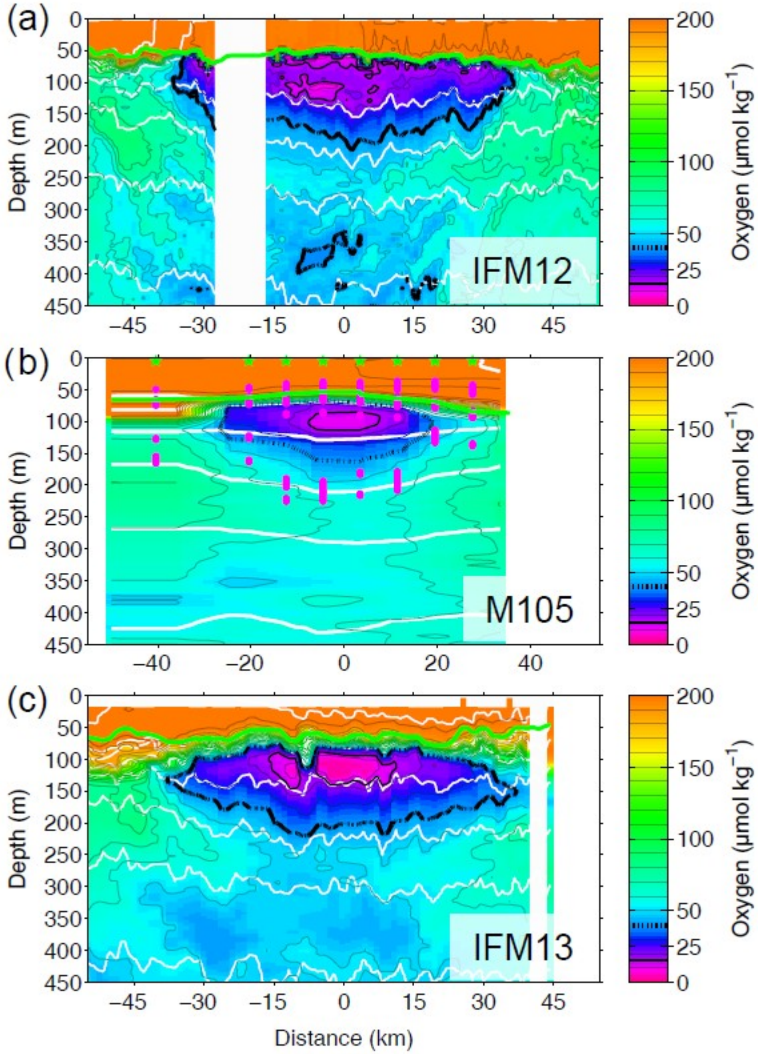


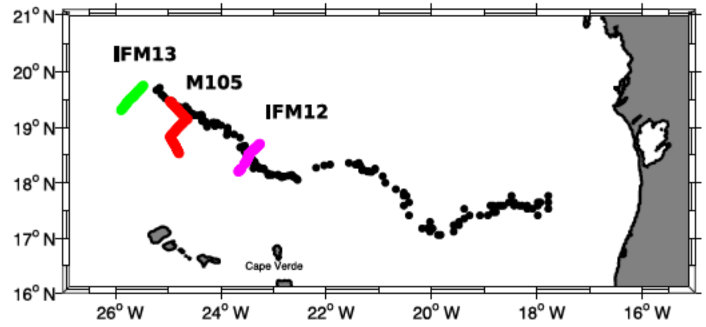


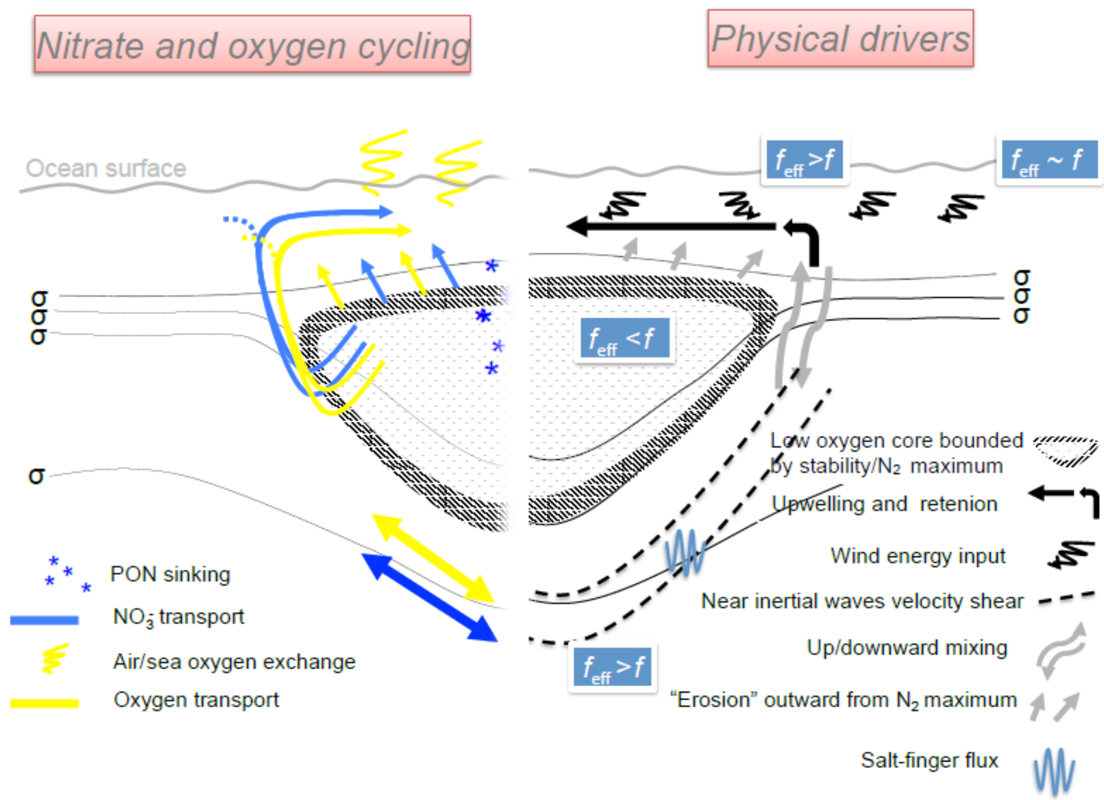
- Mean oxygen anomaly in the core depth range (50 & 150 m) for CEs (ACMEs) is 38 (79) µmol/kg
- The locally increased oxygen consumption within the eddy cores enhances the total O_2 consumption in the open ETNA Ocean and seems to be an contributor to the formation of the SOMZ.

ETNA: Dissolved oxygen and eddies

Anticyclonic Mode Water Eddy
Followed for 2 months

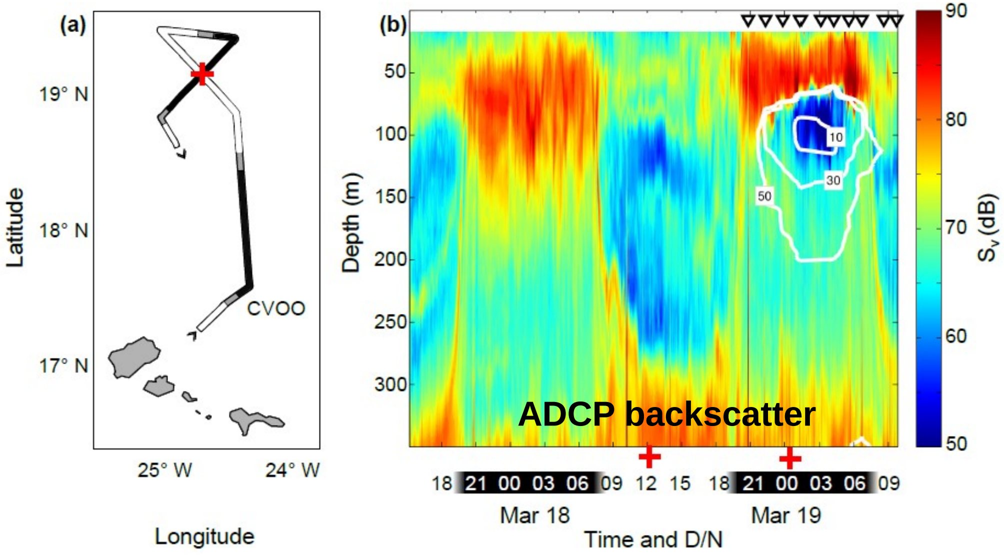




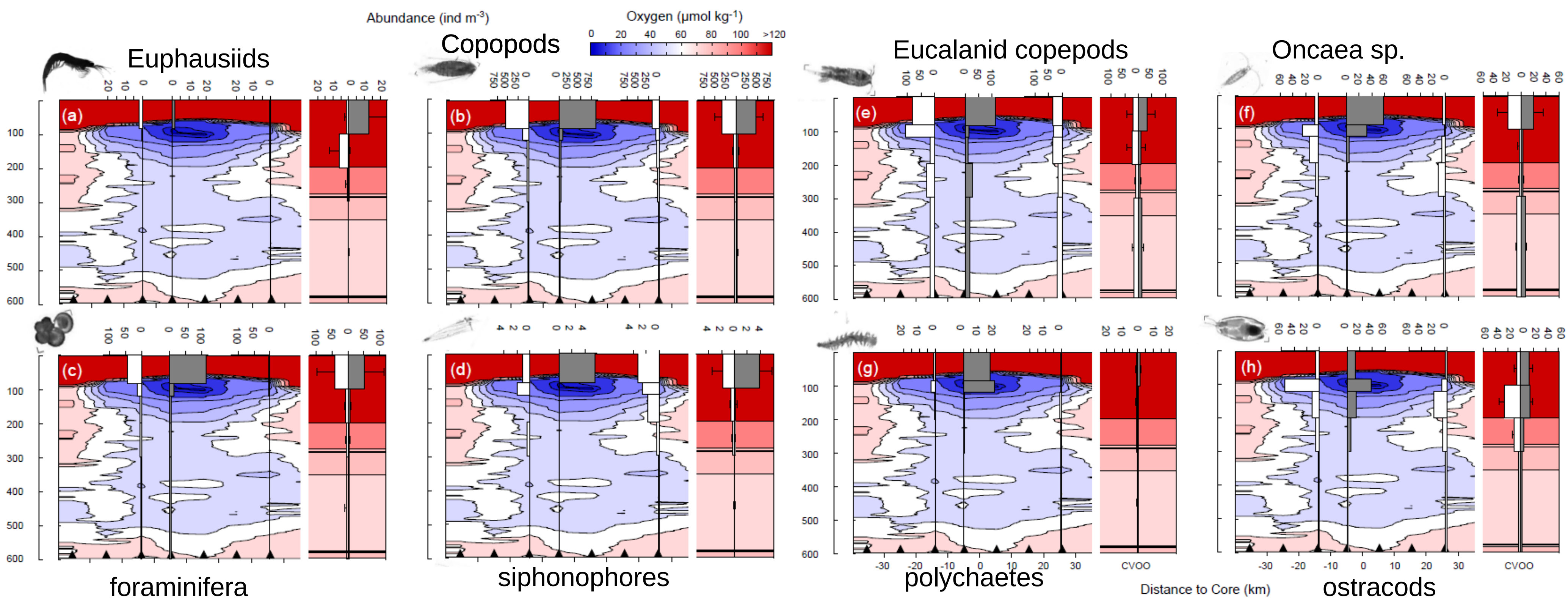


Karstensen et al., 2017

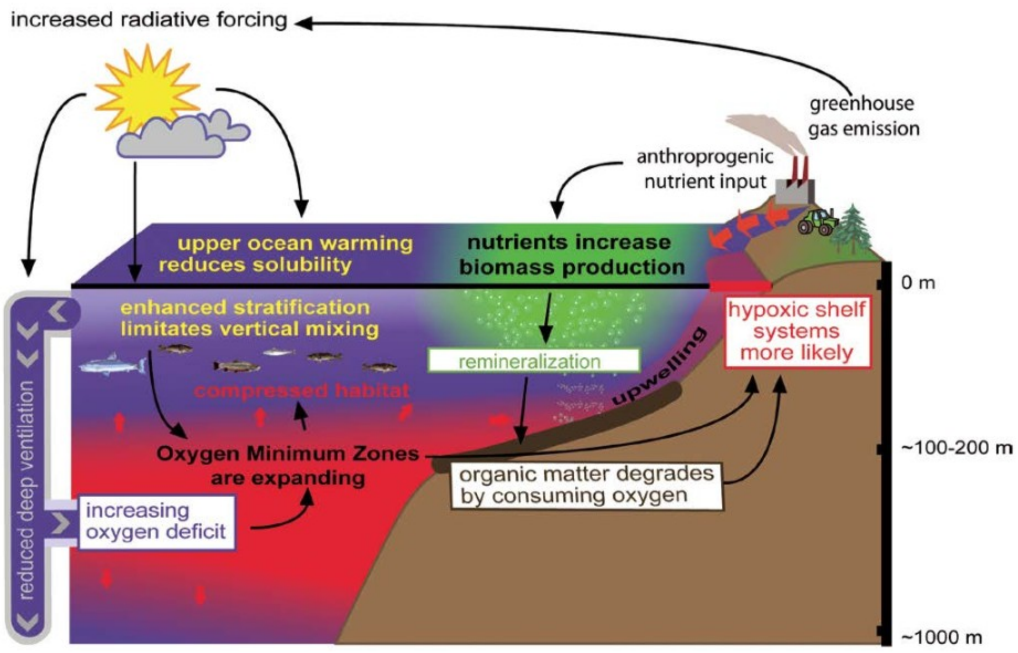
ETNA: Dissolved oxygen and eddies

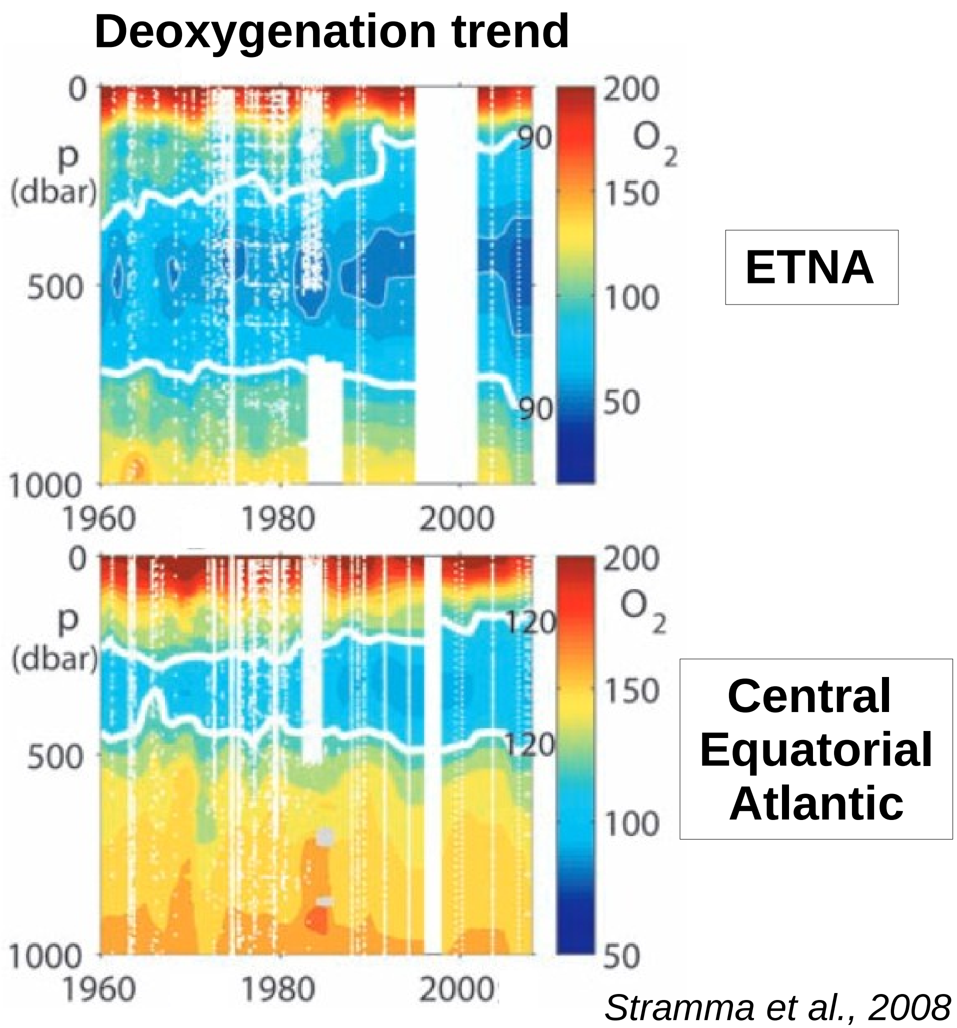


- Zooplankton avoid $[O_2] < 20$ µmol/kg
- Différentes strategies for different zooplancton communities



ETNA: Deoxygenation trend



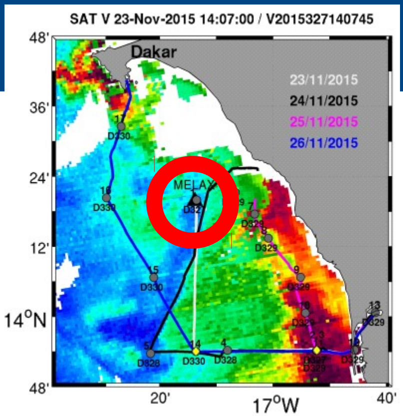


Stramma et al., 2008

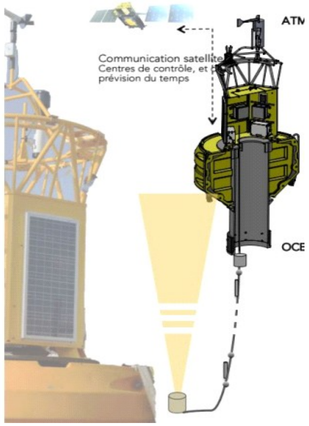
- The deoxygenation of the ETNA OMZ during recent decades suggests a substantial imbalance in the oxygen budget: about 10% of the oxygen consumption during that period was not balanced by ventilation.

- Long-term oxygen observations show variability on interannual, decadal and multidecadal timescales that can partly be attributed to circulation changes

Variability of DO over the shelf



MELAX – 28 m – 29 November 2017 to 13 December 2018



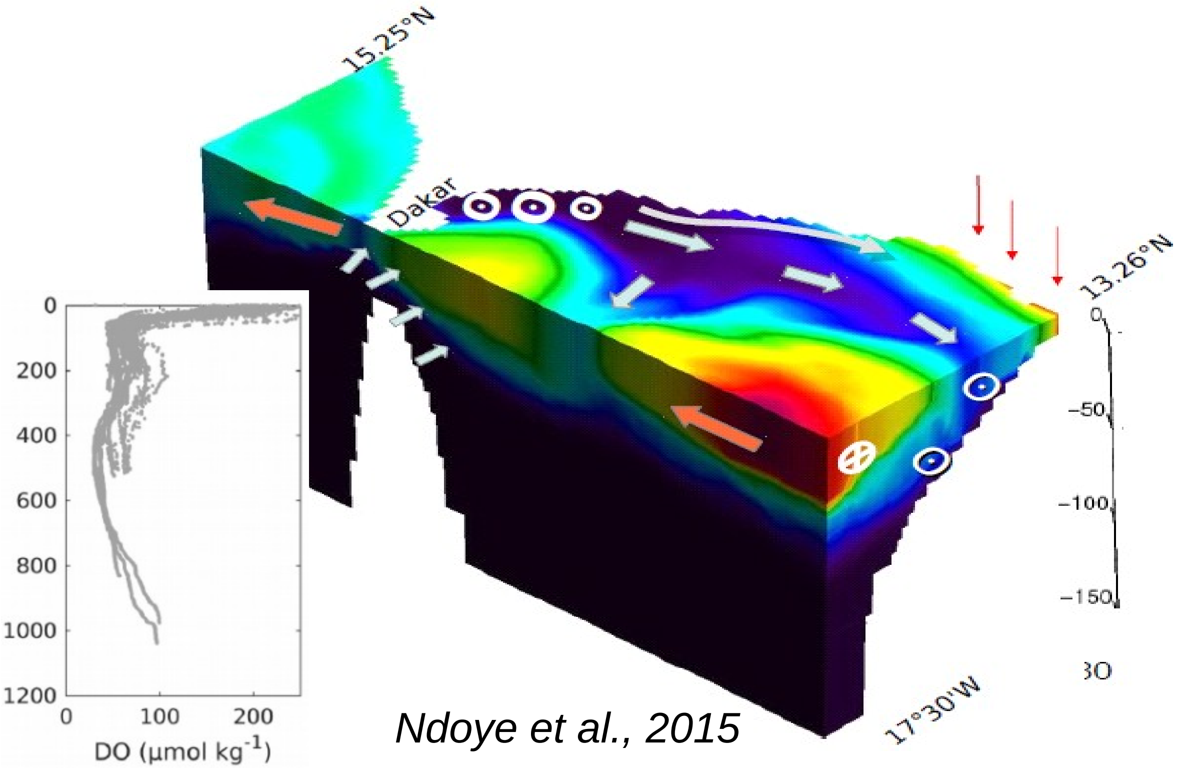
2012

Short envents of severe hypoxia

- What are the scales of variability?
- Response of dissolved oxygen to upwelling variability?
- Understand the underlying processes (multi-variable data sets, modelling)

Eastern Tropical North Atlantic: oxygen over the shelf

Open ocean preconditions DO over the shelf ...

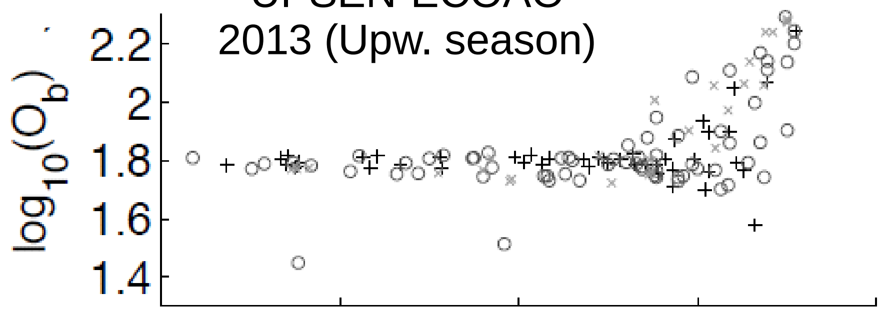


Ndoye et al., 2015

Shelf circulation
Upwelling season

- Divergence and upwelling occur mainly between south of Dakar
- The upwelling jet then transport water southward

Bottom Oxygen properties
on the shelf



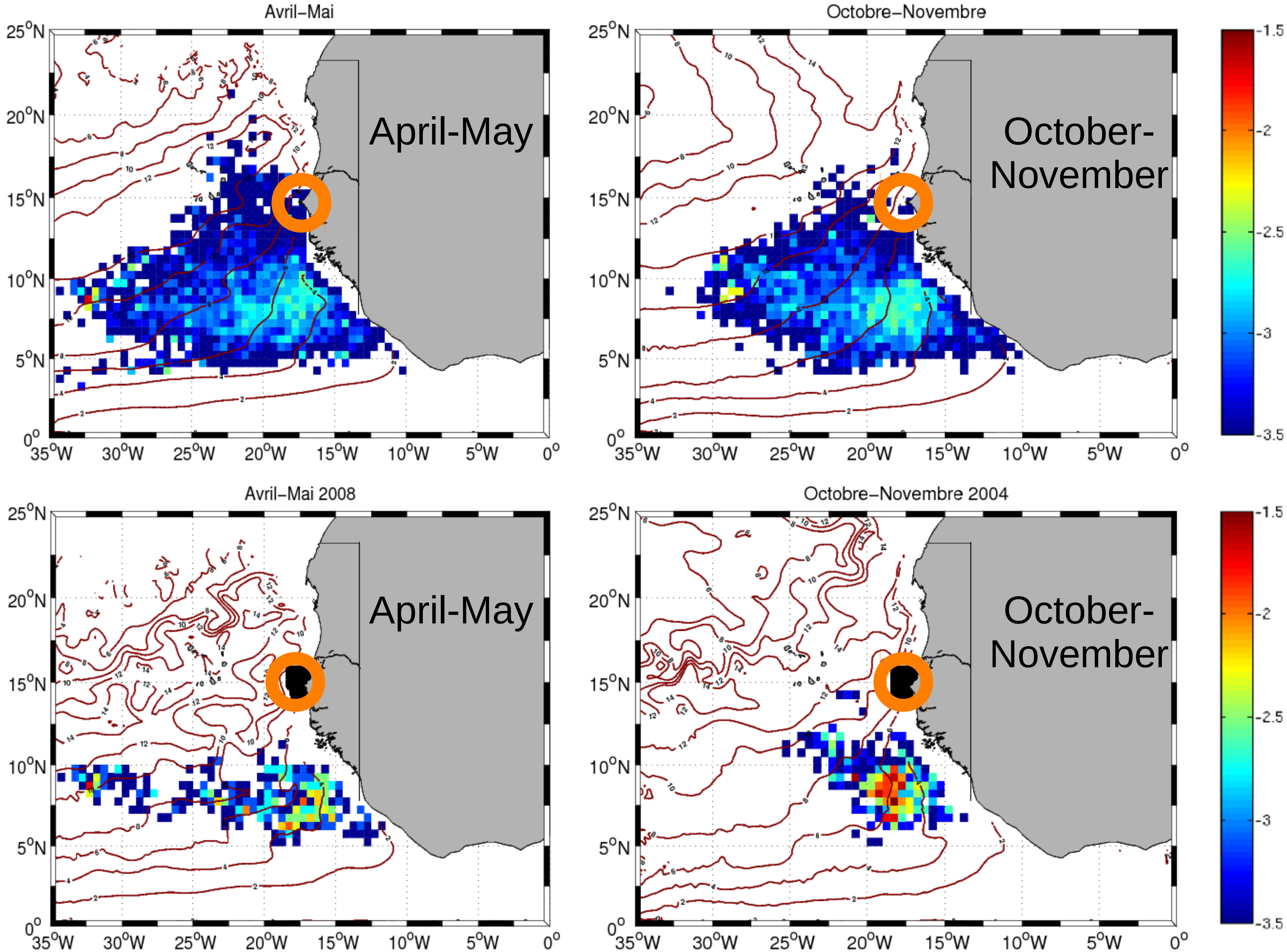
Capet et al., 2017

Eastern Tropical North Atlantic: oxygen over the shelf

Origin of water masses off the shelf of Senegal

20 years
average
of source water

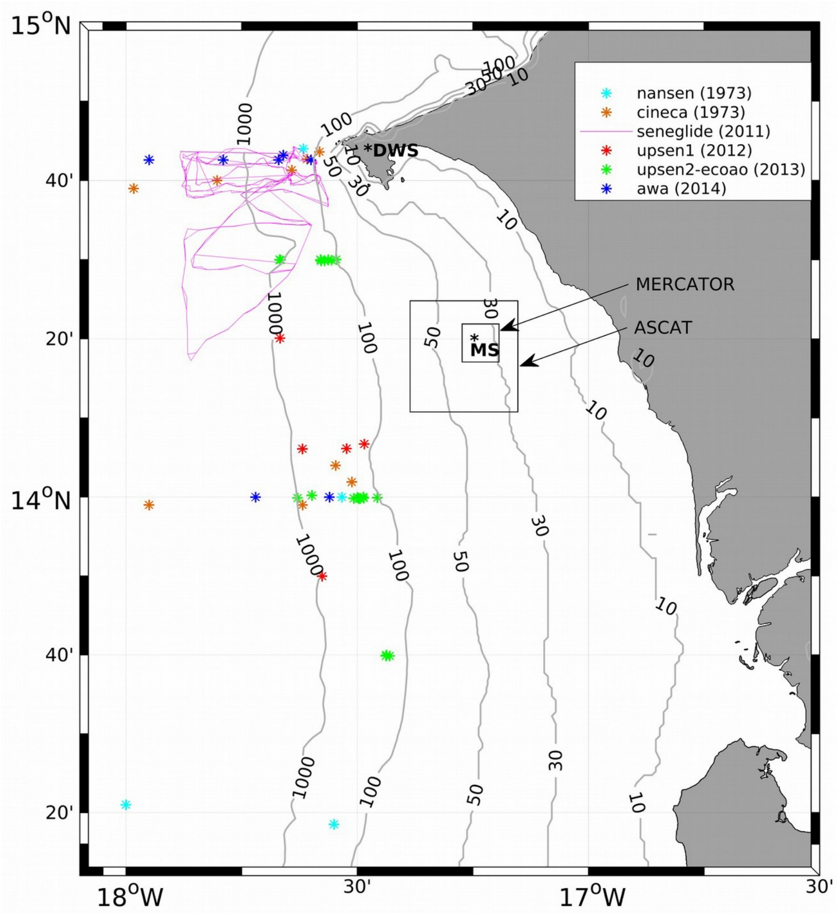
Interannual
variability
of source water



Kounta et al., 2019

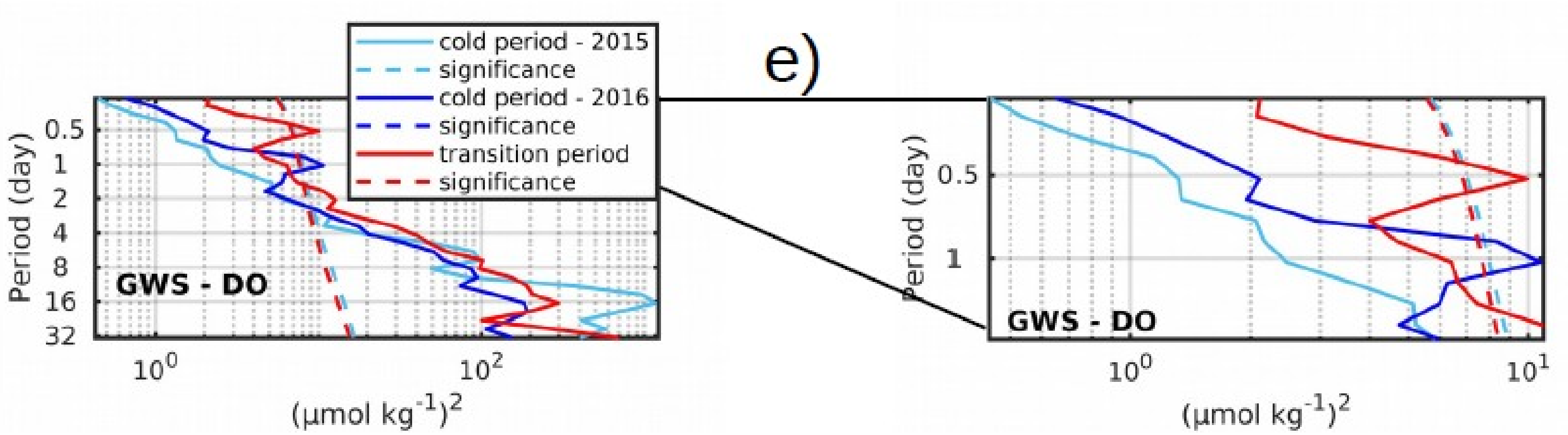
Processes affecting oxygen variability

Shallow oxygen minimum matters ...



Tall et al., in prep

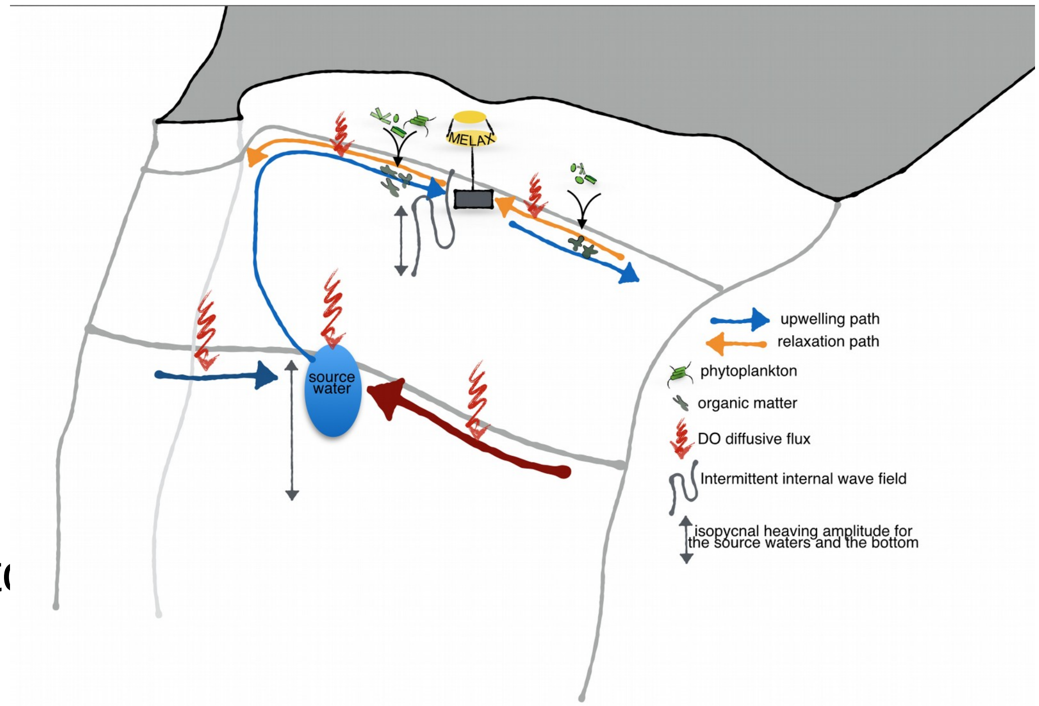
Processes affecting oxygen variability



Global Wavelet Power Spectrum of bottom layer DO at MELAX

Physical processes affecting DO

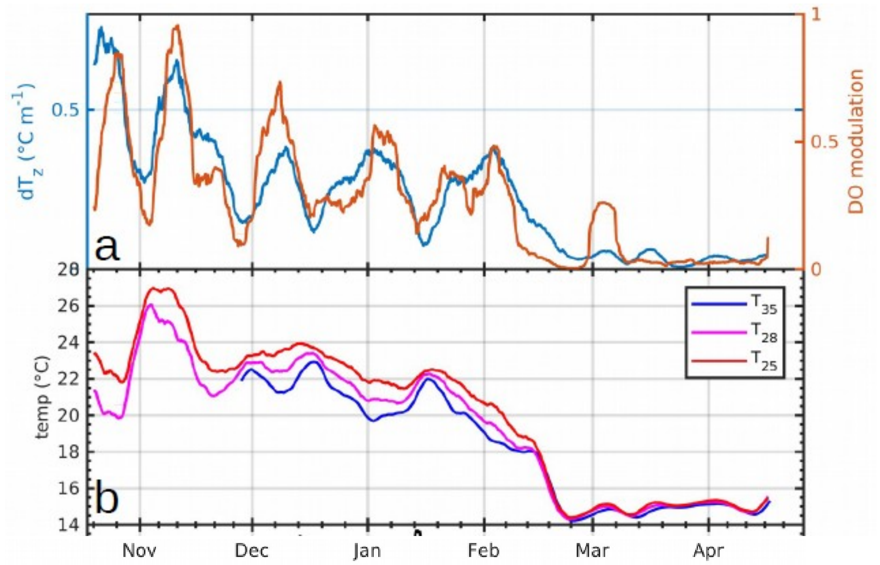
- **Seasonal time scale**: different water masses over the shelf during the upwelling or the monsoon season
- **Intraseasonal time scale**: upwelling/relaxation phases or southward versus northward currents
- **15 days time scale**: coastal trapped waves?
- **Daily time scale**: oxygenation related to wind variability
- **Semi diurnal time scale**: diffusive oxygenation induced by internal tides



Tall et al., in prep

Semi-diurnal varibility: Role of submesoscale processes

High pass filter (30h) of wind, T, S & DO

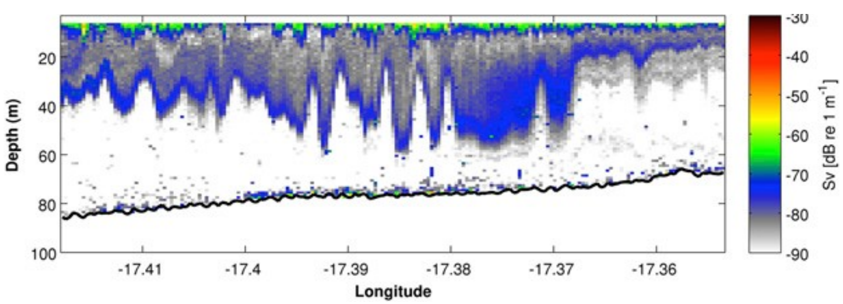


- The low frequency modulation of the high frequency variability is highly correlated to the stratification intensity
- The variations of stratification intensity are mainly forced by bottom temperature

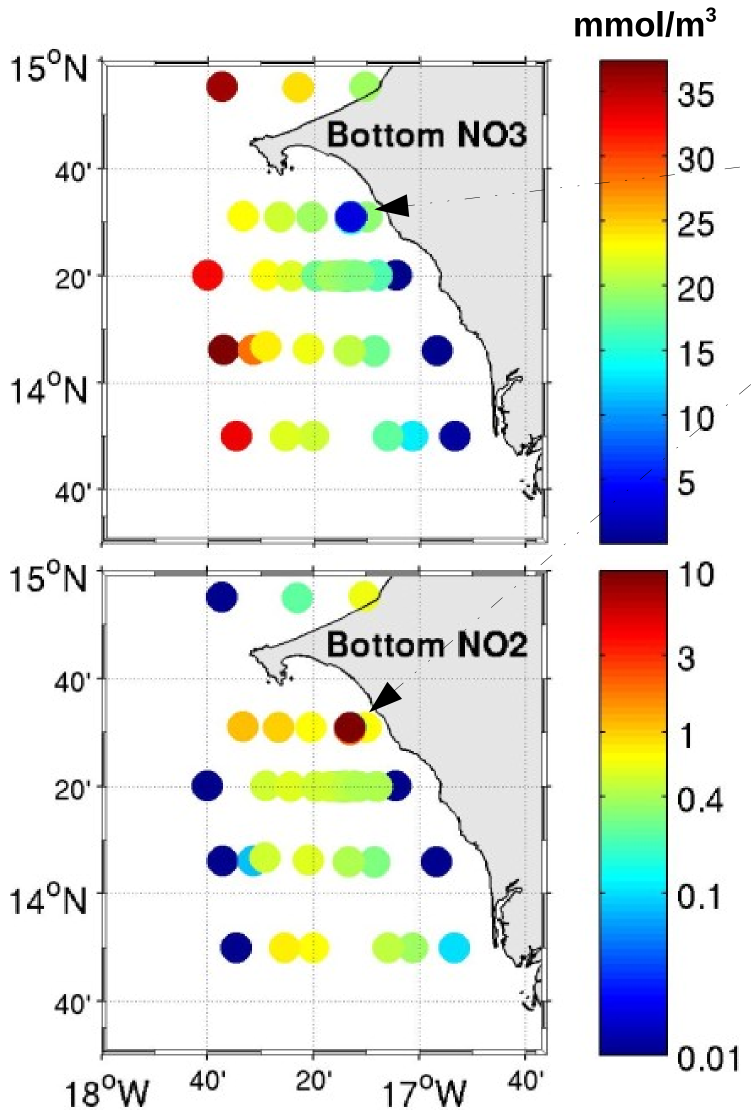
2015

2016

Acoustic signature of internal waves

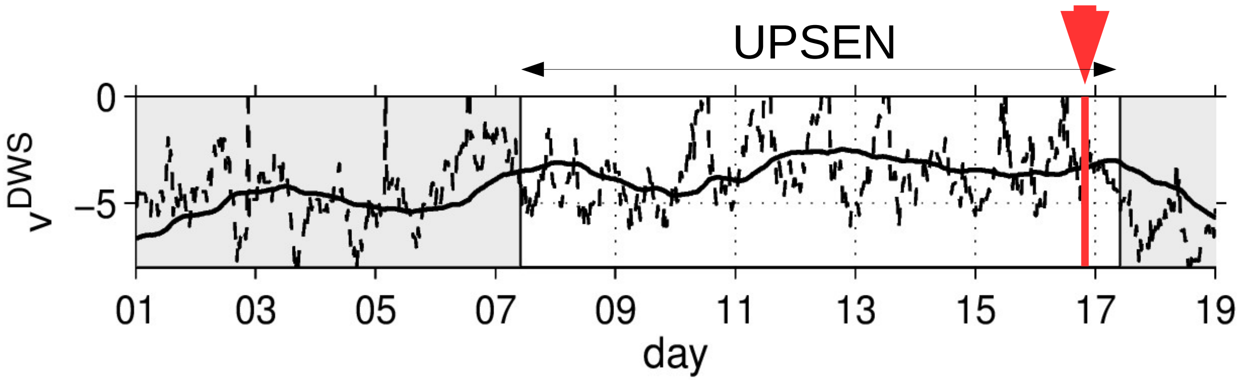


Anoxia event



Focus on stations carried out at the end of the survey (March 16th) at 14°31'N by 31 m depth

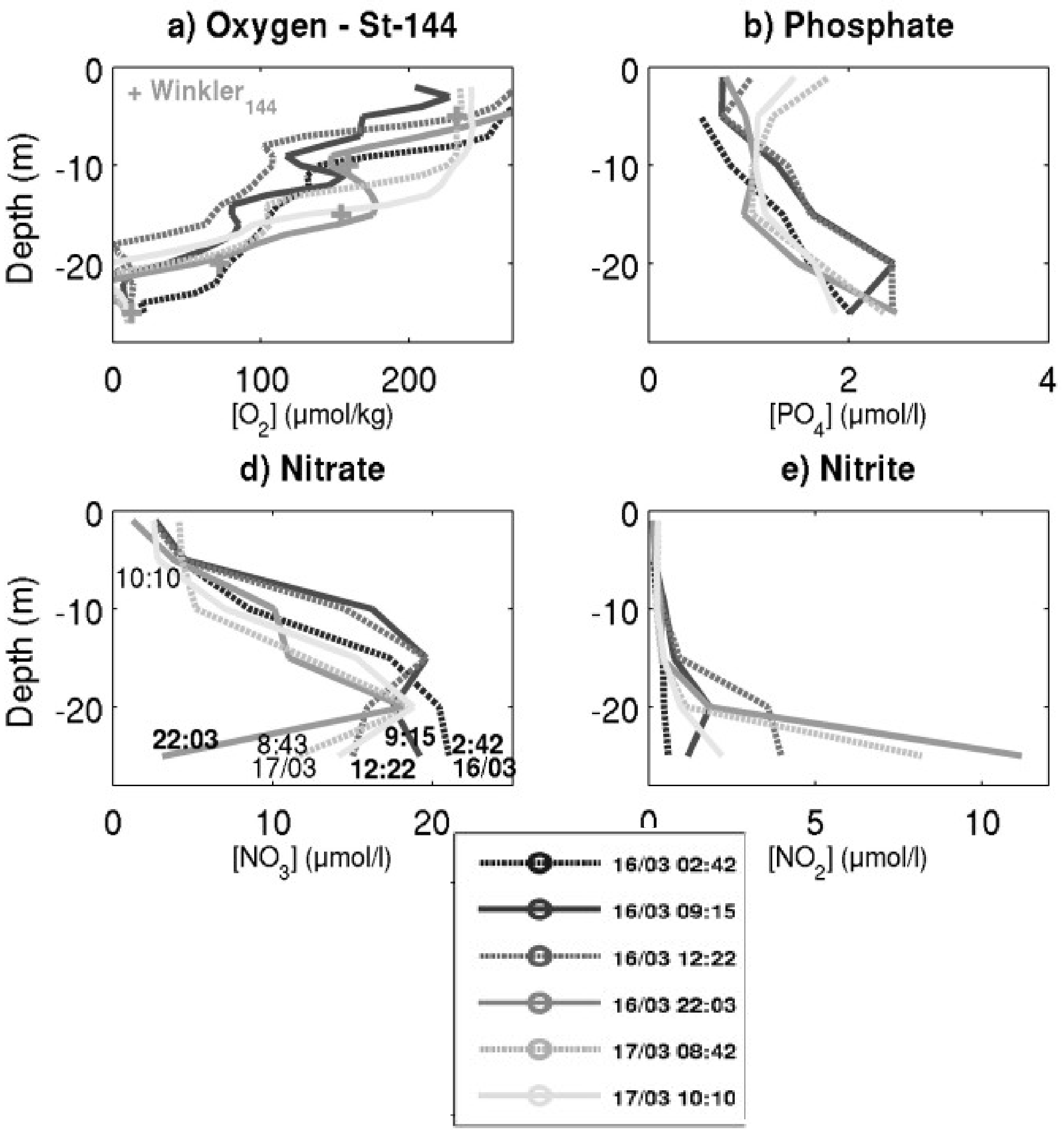
- Six stations sampled less than 1km apart
- Relaxation phase of the upwelling



Wind at Dakar Weather Station

Anoxia event

Recording of a short episode of anoxia, ~**10 m bottom layer**



6 stations sampled less than 1 km apart in ~32 h

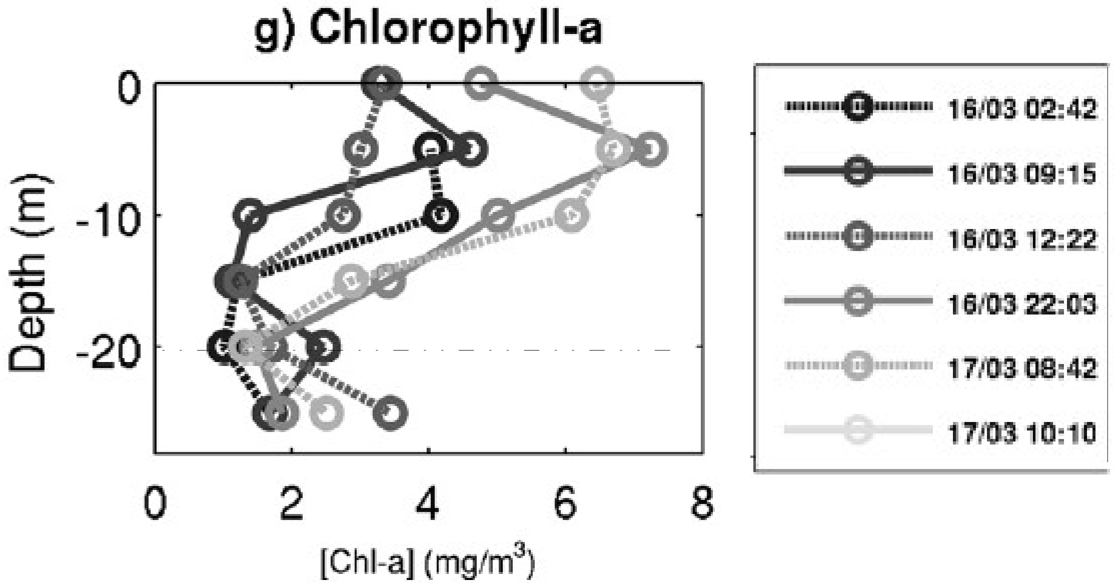
- March 16th: 2:42 am – 9:15 am – 12:22pm – 22:03pm (**Sta-144**)
- March 17th: 8:43am – 10:10am

Maximal N-deficit the 16th at 22:03 pm (Sta-144)

Very high nitrite concentrations

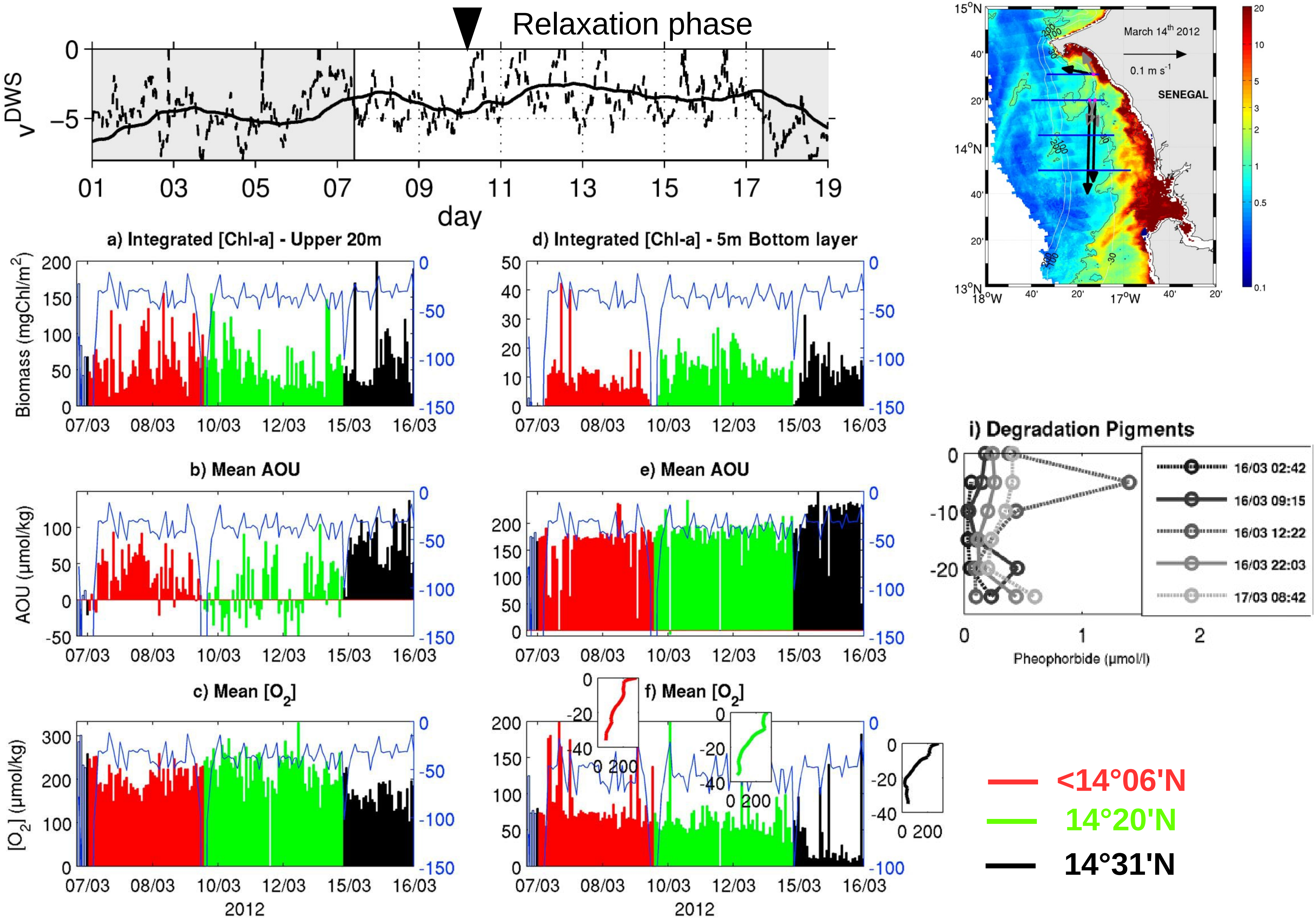
Anoxia event

- Based on DO concentrations in source waters, depleting oxygen would require the consumption of ~60 µmolO_2/kg
- Assuming a photosynthesis/respiration reaction with a typical mean C:Chl of 50, such reduction requires **10 mgChl-a/m^3**

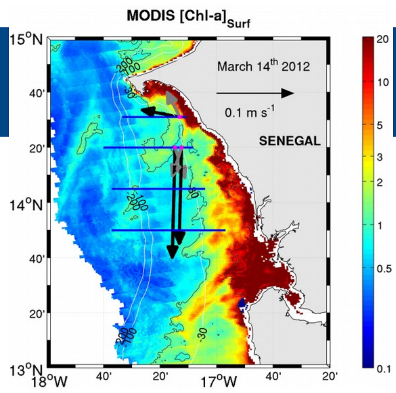


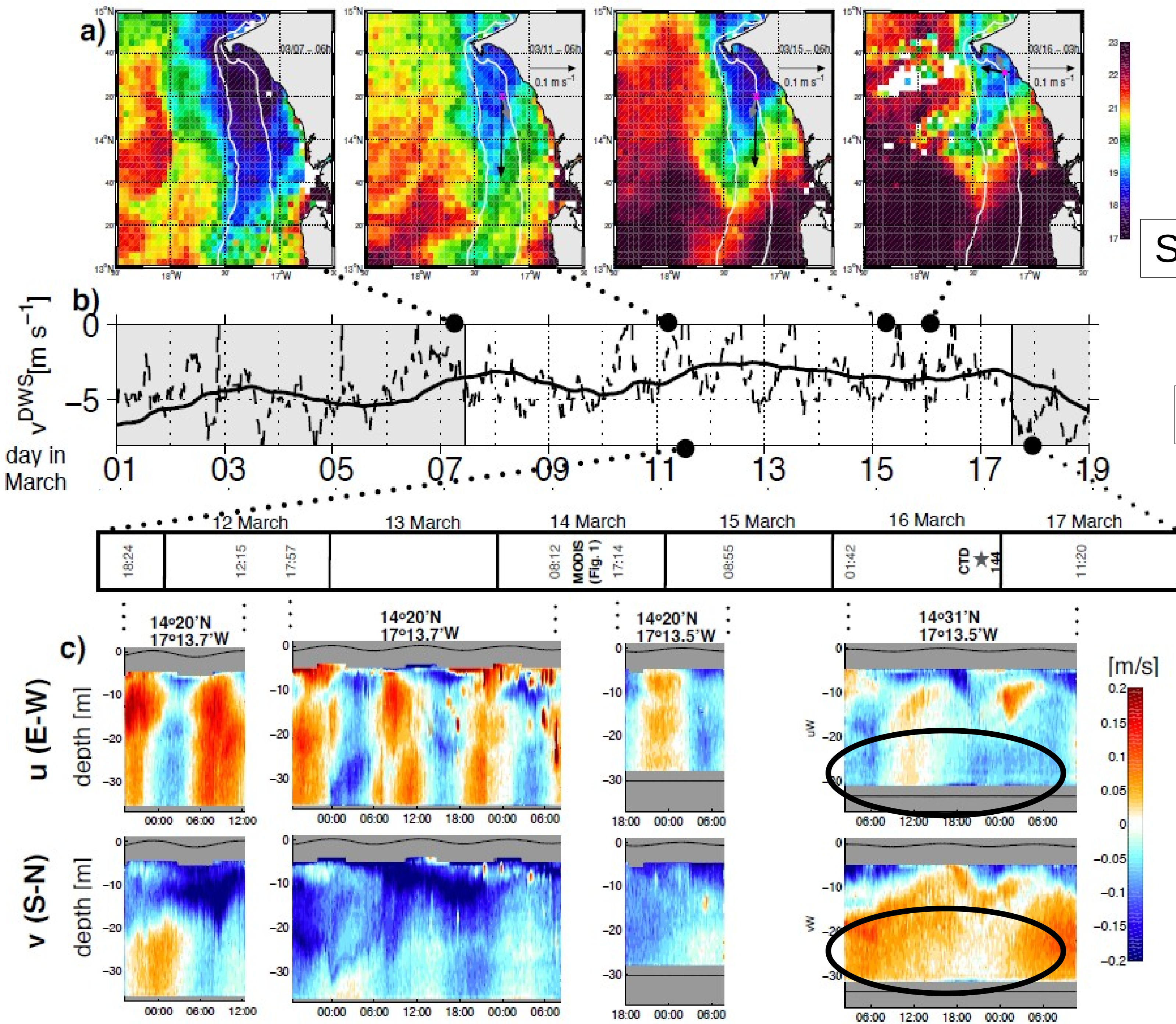
- Consumption of 60 mmol/m^3/d would be required at the sediment interface → 2 orders of magnitude higher than observations (Mauritania, Dale et al., 2014)
- 1D hypothesis fails and must imply 3D processes

Anoxia event



Anoxia event





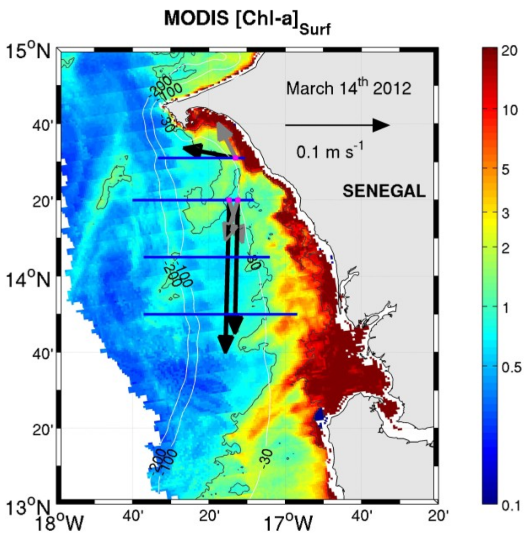
Signature of a CTW

Wind relaxation

Flow reversal

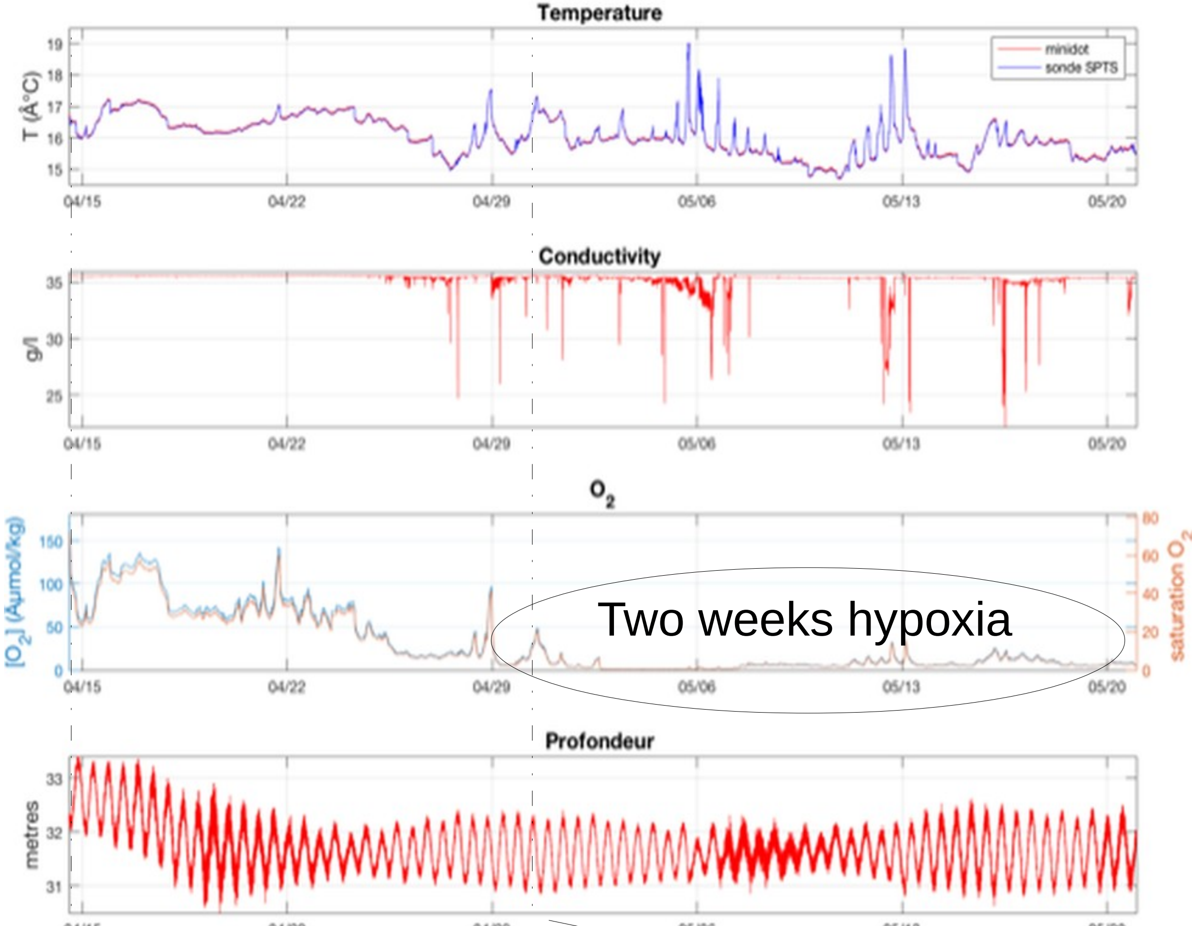
Anoxia event: Conclusion

- Summary: 3D process, relaxation & evidence of degradation, high concentrations along the coast, flow reversal
- The anoxia encountered at midshelf during an upwelling relaxation is thus the likely consequence of the advection of a decaying diatom bloom that developed in shallower waters. Similar sequences are also encountered in the Benguela and California upwelling systems.
- Remaining questions: extension and duration of this event, frequency of occurrence of such events, role of this subregion on nitrogen budget, evolution?



Dissolved oxygen and fish

Ouakam / 31m – 14 Avril to 22 May 2018



T

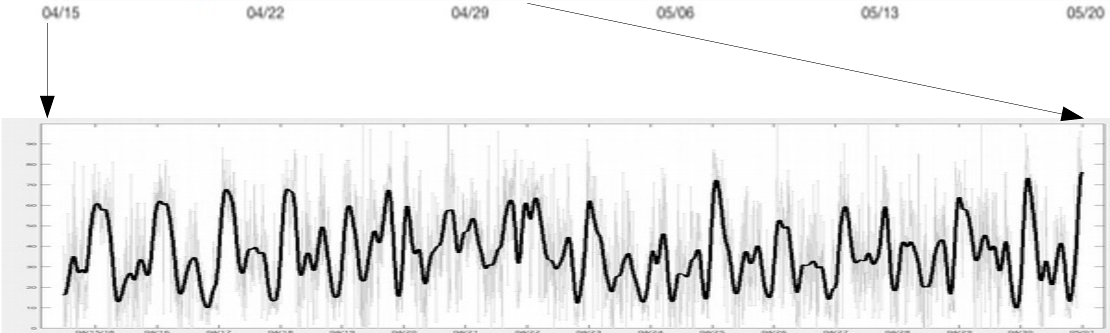
S

O2

O2 sat

P

Relationships between O2 distribution & marine resources??



Fish sound counts

Understanding variability of dissolved oxygen

Animation of O2min maps

Coupled ROMS-PISCES experiment (1/12°)

Take home message (from me) on oxygen variability in the ETNA

- The southern part of the Canary Current Upwelling System has low oxygen concentrations and raises concern about its evolution
- Oxygen variability involves many different processes at different time and space scales
- Low oxygen levels have impacts on ecosystems, and dealing with perturbation (like oxygen decline) has an energetic/metabolic cost
- We have indications of deoxygenation in the open ocean
- We do not have enough information to talk about trends in coastal waters
- The understanding of the consequences at the ecosystem level is at his infancy

If we keep behaving like we do now, we will understand what is really going on and their consequences much too late ...


Jërëjëf !